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GEOLOGICAL MAGAZINE

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Drainage and Fracture Patterns in North-West Scotland

By J. B. AUDEN

(PLATE VIII)

ABSTRACT

The drainage pattern of North-West Scotland is considered in relation to already known and newly inferred fracture zones, and it is concluded that a system of Tertiary fractures, connected with the plutonic centres of the Western Isles, has been superimposed on the rhombic pattern of late-Caledonian faulting.

I. INTRODUCTION

IN a recent paper to the *Geological Magazine* an attempt was made by the writer to relate certain topographical expressions in peninsular India to fracture patterns (1954, p. 89). It is now proposed to consider the disposition of streams, glens, lochs, and coastlines, in North-West Scotland, where already much evidence is available regarding faults and other fractures from detailed studies undertaken by the Geological Survey of Great Britain.

A study of the quarter-inch and one-inch topographical sheets of the Ordnance Survey was made, followed by a visit to certain areas between Fort William, Ardnamurchan, and Morar. My thanks are due to the staff in the map room of the Royal Geographical Society for much assistance in producing topographical and other maps.

II. EXISTING INFORMATION

Numerous references exist in the literature to the importance of faults, and shatter or crush belts, in the development of Scottish scenery. Peach and Horne, in their analysis of the origin of the Scottish lakes, show nine major N.E.–S.W. fault zones traversing the northern and Grampian highlands, and the Loch Maree fault, 35 miles in length, running N.W.–S.E. They attributed Lochs Ericht, Garry (Tay), Maree, Ness, Shiel, Tilt, Treig, and Tulla (to mention the more prominent lakes) to excavation along faults or shatter zones. In the main, however, they considered that many of the major lakes are rock basins unconnected with faults or shatters. Thus, Loch Morar, the

bottom of which is 987 feet below sea level, is regarded as a typical rock basin, evidently ice-formed. Gregory (1913), on the other hand, suggested that recent faults and shatters play an important part in the origin of the lochs and fjords, and in the small-scale map on page 156 of his book he shows a polygonal pattern of topographical features, including sea and inland lochs, which was possibly intended to represent the fault pattern. In the case of the phenomenally deep hollow of Morar he assumes that excavation occurred along two major dislocations. It is evident that he considers this pattern to represent a system of recent fractures.

Bailey, while accepting that depressions such as those of Loch Linnhe, Loch Leven, and the pass between Buachaille Etive More and Buachaille Etive Beag, have been excavated along fault-shattered rock (1934, p. 324), tends to doubt Gregory's assumption of recent faulting. He writes that to most geologists there is:—

> " no reason for supposing that a fault or a joint is recent just because it influences modern scenery. We know by experience that a structure may lie dormant for untold ages, until its opportunity arises . . .
>
> It is also certain that many of our great valleys have not been located by any special shattering of the solid rock " (p. 325).

The case of the small loch of Coruisk, in Skye, is cited, which Harker had shown to be carved out of rock devoid of faulting or shattering.

Two problems are, in fact, involved. First, whether or not faulting and shatter zones do in considerable measure determine the formation of many of the topographical characteristics of North-Western Scotland, to a greater extent than has been recognized by most geologists. Second, the periods during which the known faults and shatter belts originated.

The Great Glen, running in a straight line from the Moray Firth to Loch Linnhe, has long been recognized as following a major dislocation, and was recently the subject of a special study by W. Q. Kennedy. That author suggested in 1939 (although his paper was not published until 1946), that a horizontal shift of 65 miles has taken place along the Great Glen fault, causing the separation of a postulated former single mass of granite, of Lower Old Red Sandstone age, into the two distinct present outcrops of Strontian–Morven and Foyers. This fault should continue south-westwards into Donegal, in the north of Ireland, but no comparable structure appears to have been observed there. J. G. C. Anderson (1954, p. 418) has shown the existence of numerous N.E.–S.W. faults in the Slieve League promontory, but not even that which displaces the Blue Stack granite could really be considered as homologous to the Great Glen Structure. Regardless,

however, of any variations in magnitude of horizontal displacement that may exist along different reaches of the Great Glen fault (and somewhere it must die out or be replaced by a system of minor parallel fractures), this fault zone is unquestionably one of the dominant features of Scotland. It is younger than the Caledonian orogeny, and the principal movements along it are thought by Kennedy to have been mid-Devonian.

A series of five major faults or crush belts has been mapped by the Geological Survey within the Dalradians on the south-east side of the Great Glen fault, orientated N.N.E.–S.S.W., roughly parallel to the Great Glen, and oblique to the Highland Boundary Fault. On the north-west side of the Great Glen, Peach, Horne, and Kennedy have shown the presence of two similarly orientated faults, those of Strathglass and Strathconon, though it would appear to the writer that these have been unduly simplified in fig. 4 of Kennedy's paper. An *échelon* disposition is more likely to exist along certain reaches of these dislocations, particularly that between Loch Shiel and Strathglass. Only a portion of these faults is shown on the latest edition of the Geological Map of Great Britain.

Numerous fractures are delineated on plate vii, opposite page 85 of the 1952 reprint of *British Regional Geology : The Northern Highlands*, particularly a cluster of east–west crush zones in Knoydard, north of Morar, and the N.W.–S.E. Maree fault, recognized some years before by Peach and Horne.

Finally, Richey remarks on page 118 of the Ardnamurchan Memoir that late faults and crush lines traverse all the geological formations in Ardnamurchan, including the latest ring dykes, and shows that the majority of the features are simple lines of crushing, without movement. He continues significantly that the presence of many crush zones is indicated by the north-west and N.N.W. direction of the drainage system and straight-running hollows.

Here, indeed, in Scotland is an area where the existence of major faults and shatter belts is already well established. Yet it seems that the phenomenon has not been discussed on its own merits, but in general almost incidentally, as if it were of subsidiary interest to the major tectonics of the region. It is possible that a more thorough study of the fracture system present in North-West Scotland may yield results of considerable tectonic interest.

The known faults and crush zones all follow recognizable topographical features, so much so that it was possible to anticipate long stretches of their alignments from the Ordnance Survey maps, without previous reference to the published geological data. It is this close relationship, between clearly orientated topographical depressions and already established faults, which has suggested that fault or

crush zones probably also exist along other analogous lines of depression, provided the possibility of parallelism with the regional strike of the geological formation is eliminated. Such a relationship, which had at first been deduced from a study of the topographical maps in peninsular India, has been subsequently proved to exist by the unequivocal evidence of engineering excavation.

III. Examination of the Topographical Maps

An examination has consequently been made of the Ordnance Survey maps of North-West Scotland, with the object of demarcating such orientated alignments of the drainage pattern as appear not to be fortuitous, but to possess some latent structural significance. The assumption is thus no more than that the highly characteristic drainage system of that region is there to guide the geologist, and that a careful study of the topographical maps does provide information about tectonic developments which tends normally to be obscured by the bewildering complexity of inversions, lags, and metamorphic variations, arising from the Caledonian orogenesis. It appears that such a procedure does disclose the existence of a more general pattern of post-orogenic fractures (or, if that is held to beg the question, of orientated erosional phenomena) than is recognized in most of the literature and geological maps. As examples may be cited the W.N.W. extensions of the Loch More and Loch Assynt faults as lines of weakness up Strath Stack and Loch Poll, and the N.W.–S.E. feature which runs from Rudh' an Fhir Leithe to Loch Inchard and Loch Stack. In the Outer Hebrides there is also a very striking development of inland lochs, streams, and deeply serrated coastline, which appears to link up that Archaean remnant with the much younger tectonic events of the inner volcanic isles.

The reason for this is evident, and has already been remarked on. The field geologist's attention is at once aroused by planes of faulting along which displacement of geological boundaries has occurred. Shatters which are unaccompanied by displacement tend, on the other hand, to be regarded as minor phenomena of secondary importance, and in some small areas of study this might in fact be legitimate. But when the suspected fractures are plotted regionally, a new group significance appears to ensue from their geometric and tectonic relationships.

Further, an altogether different emphasis regarding these faults and shatter zones arises in the case of engineering construction, whether this be in India or Scotland, and a firm of engineering consultants recently informed me that the majority of dams constructed in the Scottish Highlands were located across faults or shatters. Unfortunately it has not been possible to pursue that aspect of the phenomenon

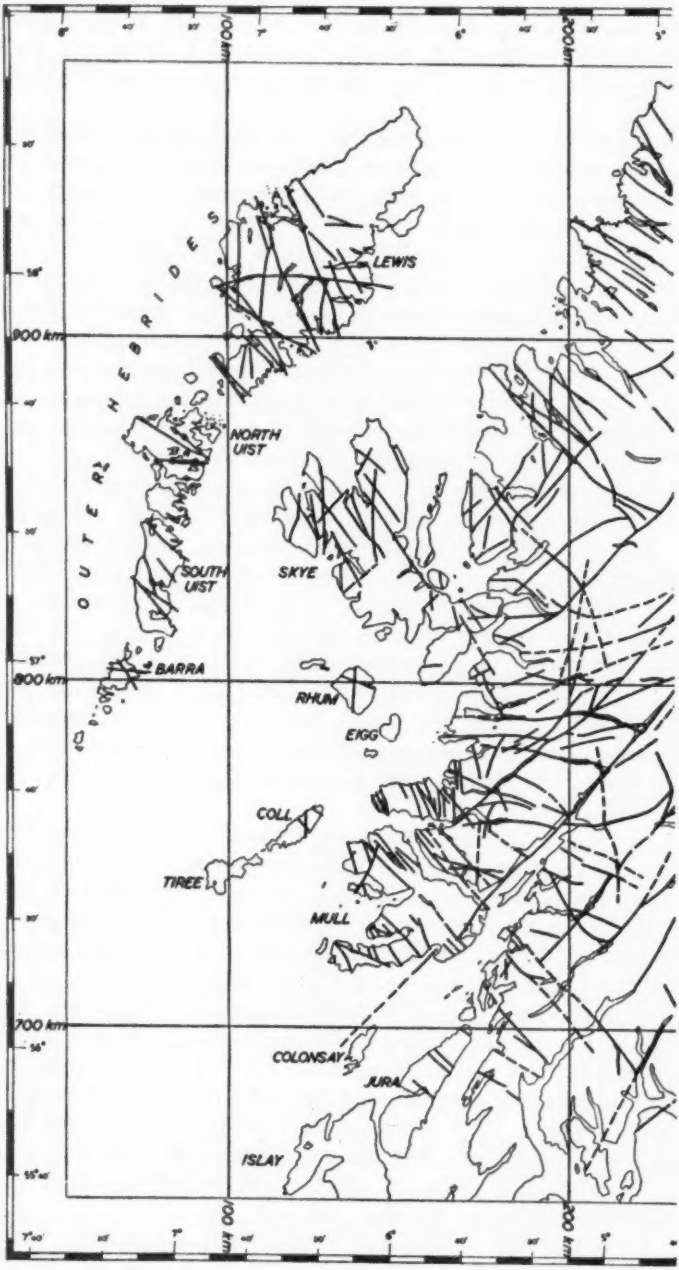
or to confirm the deductions drawn from the maps by details obtained from recent engineering projects. It may be hazarded that the dam across the north end of Loch Treig very probably encountered shattered rock.

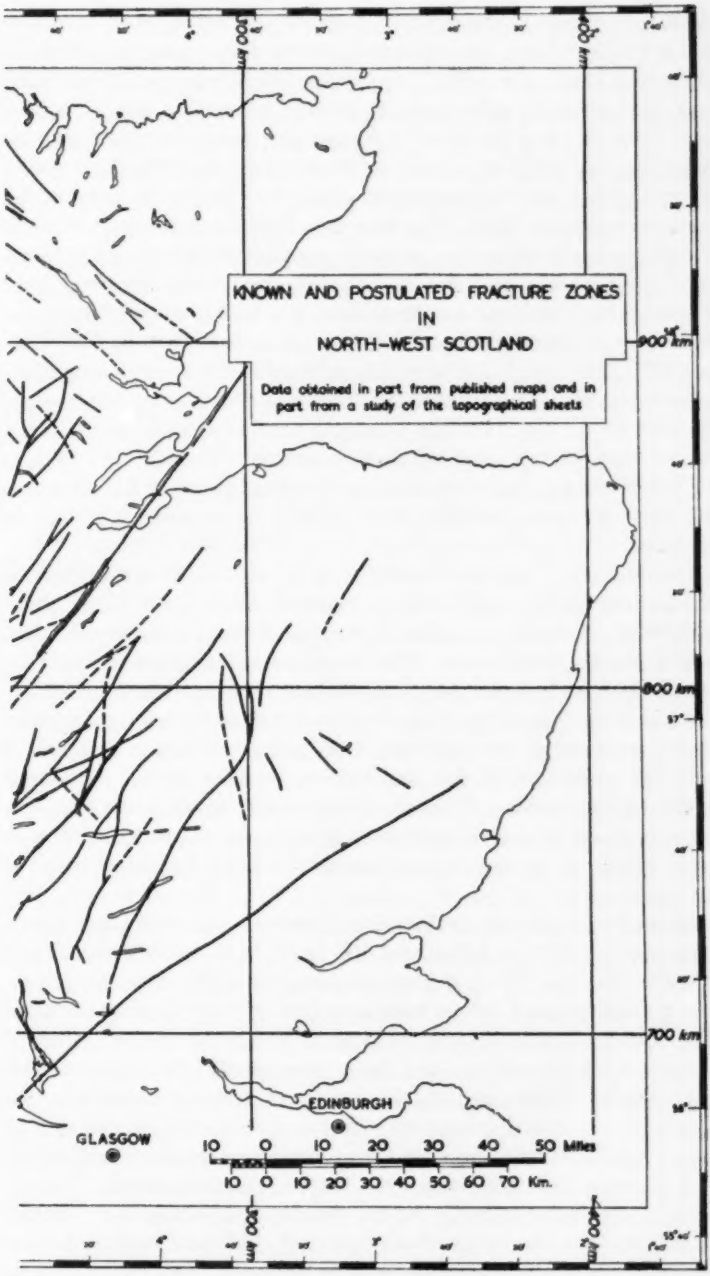
The results of this examination of the topographical sheets, as well as of published geological data, are shown on the map accompanying this paper. The lines on this map are interpreted as fractures, and no attempt has been made to indicate whether or not significant net displacements have occurred along them. This map is put forward with some diffidence, the more so because the shortness of my stay in Britain made it impossible to check more than a few of the postulated fracture zones. Even allowing for some degree of possible unconscious selection of alignments favourable to an hypothesis, the pattern disclosed by the map appears to be logical and not capricious, and to demonstrate a relationship between some of the fractures and the Tertiary volcanic phenomena. Field examination will determine to what extent this may be nothing more than verisimilitude, lacking substantive connection with the tectonics of Tertiary vulcanism.

The extensions of known faults may not involve displacement of formations, but rather shattering. In other cases it is probable that the whole postulated fracture is no more than a major shear zone, without displacement but with considerable shattering. No attempt has been made to date the phenomena, but it is at once evident that some of the fractures, such as the Great Glen system, are ancient (Kennedy), whereas the closely spaced fractures intersecting the Tertiary lavas and post-lava plutonic centres are not older than Eocene. Consequently, there is a range of age from late Caledonian to early Tertiary.

Not all the features which are assumed to be fractures possess the same clarity, as delineated on the topographical maps, or a uniform conviction of continuity. Those in the small circumscribed area of Ardnamurchan are prominent and have already been recognized as shatters by Richey. The topographical features in Western Sutherland which are orientated W.N.W.–E.S.E. are also pronounced, and would seem to provide a reasonably certain indication of fracturing. Others have been suspected because of the occurrences of narrow ravines or gulches, such as that at the eastern end of Loch Arkaig by Prince Charlie's tree, and another along the road 4 miles south-west of Salen. In one instance, north of Bellsgrove, Strontian, old workings along a lead vein emphasize a prominent east–west lode situated in granite, and extending for 4 miles, which is indisputably accompanied by shattering and gouge material. (Pl. VIII, fig. 1.)

It is not possible to discuss the various features regarded as fractures within the imposed space limitations, but two cases may be briefly


LEWIS
OUTER HEBRIDES
NORTH UIST
SOUTH UIST
SKYE
BARRA
RHUM
EIGG
COLL
TIREE
MULL
COLONSAY
JURA
ISLAY
900 km
800 km
700 km


KNOWN AND POSTULATED FRACTURE ZONES
IN
NORTH-WEST SCOTLAND
Data obtained in part from published maps and in part from a study of the topographical sheets
900 km
800 km
700 km
EDINBURGH
GLASGOW
10 0 10 20 30 40 50 Miles
10 0 10 20 30 40 50 60 70 Km.

mentioned. Loch Morar certainly presents a problem. With a bottom that is 987 feet below sea level, and thus so deeply excavated into the continental shelf, it is difficult to suppose that ice erosion alone could have been effective unless greatly assisted by weak zones. Yet it is clear from the detailed work of Richey and Kennedy (1939) that no major faulting exists on a scale sufficient to displace the great variety of lithological and metamorphic types, so eminently suitable for showing boundary shifts. The lake cuts right through the formations at right angles to the strike. A brief examination of the Upper Psammitic group in the field shows, however, that in the neighbourhood of Traigh and Maol na Readhra, there is a highly developed vertical sheet jointing orientated east–west (the range being between 80°–260° and 105°–285°) which almost simulated bedding until the characteristic current bedding demonstrated the true steep formational dip towards the west or W.N.W. On the foreshore near Traigh House there is a shatter zone 12 feet wide which is orientated 70°–250°. At least in the Upper Psammitic group there are grounds therefore for regarding this very prevalent vertical sheet jointing as a possible source of weakness.

The Morar excavation is parallel to a very clear line of narrow depressions, gullies, and lochs, extending from 1,400 yards south of Arisaig eastwards to Lochs Mama and Beoraid and Glen Finnan, over a distance of 19 miles. This must surely indicate a shatter belt, even though no boundary displacements are shown to exist by Richey and Kennedy. Steep dips in a southerly direction by grid co-ordinates 706850 of Scottish one-inch sheet 46 suggest indeed a fracture of sufficient magnitude in the Sub-Moines to have caused distortions in the regional strike. Consequently, notwithstanding the apparent absence of any major vertical faulting, there are many indications in south Morar of an east–west structural weakness involving much of the Moines.

Another example may be mentioned from the shore of Loch Sunart 2,900 yards E.S.E. of Salen, and 800 yards W.S.W. of Resipol (grid 715640). The true dip of the Moine granulites is 80° east. The granulites are cut through by an intense system of sheet joints orientated N.E.–S.W. to E.N.E.–W.S.W. parallel to an almost certain system of shatters which pass from Loch Shiel, over Meall Mhic Chiarain and down Allt Mhic Chiarain, into Loch Sunart. Other fractures are seen from a distance cutting near the summit of Ben Resipol, and one of these presumably joins up with the east–west mineralized shatter-vein of Bellsgrove, Strontian, which has been referred to above. Cutting through the whole complex on the Sunart shore there is a Tertiary basalt dyke 26 inches wide which runs 300°–120° and is accompanied on either side by sheet jointing 28–33 inches wide. This exposure is of

interest in showing that the Resipol fractures parallel to the Shiel-Sunart direction are pre-dyke, and that the Moines have succumbed to the following events: metamorphism; extensive sheet jointing parallel to the Shiel-Sunart direction of dislocation; localized sheet jointing parallel to the Tertiary basalt dyke. (Pl. VIII, fig. 2.)

Further east, on the south shore of Sunart and running north–south down the slopes of Beinn nam Beathrach, there are pronounced narrow gullies which are strongly indicative of fractures. In this Sunart area there are therefore at least three sets of major fractures:—

(1) E.N.E.–W.S.W. or N.E.–S.W.	Major system of Shiel-Sunart, probably related to the late-Caledonian Great Glen Fault.
(2) N.W.–S.E. . .	These fractures cut the Tertiary lavas and plutonic rocks, and are of Tertiary age.
(3) North–South .	Conspicuous in Skye cutting Tertiary plateau basalts, and probably of Tertiary age even in areas where only pre-Cambrian rocks are affected.

IV. Discussion of Scottish Features

The topographical features which are thought to be indicative of fractures, and the already known faults, are shown on the map accompanying this paper. The results may be summarized as follows:—

(*a*) In the centre of the area the dominant feature is the rhombic pattern represented by:—

(i) The N.E.–S.W. fracture system of the Great Glen, together with those of Loch Shiel and Loch Loyne.

(ii) The east–west fracture system represented by Lochs Sunart, Eilt-Eil, Morar, and Arkaig.

Movement along the Great Glen fault is considered by Kennedy to have ended in Carboniferous times, and to have been at a maximum during the period of deposition of the Middle Old Red Sandstone. Presumably the faults and shatters which are parallel to the Great Glen, as well as the east–west set participating in the rhombic pattern, originated then, as a post-orogenic block system.

(*b*) In Sutherland, Easter Ross, and Cromarty, the dominant fractures are W.N.W.–E.S.E. These fractures cut the Caledonian granites, and may first have originated shortly after the Caledonian orogeny, simultaneously with the Great Glen fault.

(*c*) There are also, however, N.W.–S.E. fractures in the western isles which most clearly cut the Tertiary basalts of Skye, Ardnamurchan, Morven, and Mull. These fractures are therefore post lava, and, indeed, as shown by Richey, post ring-dyke. Those in western Ardnamurchan are seen to cut

hypersthene-gabbro and quartz-dolerite veined with granophyre. These fractures are parallel to the direction of the dyke swarms.

(*d*) There is a fairly well pronounced set of north–south fractures in Lewis, north-western Skye, and eastern Ardnamurchan. This is post-lava in the area of the plateau basalts, and one fracture in Rhum cuts through the ultra-basic plutonic rocks. Since the pattern in the Archaean area of Lewis closely resembles that in the Tertiary volcanic islands, it is possible that the Lewis fractures are also of Tertiary date.

(*e*) In the mainland, bordering Skye, Rhum, Eigg, and Mull, there appears to be a radial pattern of fractures converging on a centre in the neighbourhood of Eigg. This suggests some connection with an igneous centre where the plutonic phase may be concealed under the lavas of Eigg and the sea.

(*f*) In the Highland block north-west of the Great Glen fault there is a suggestion of regionally arcuate fractures encircling the hypothetical Eigg centre. The coastline of north Ardnamurchan, Moidart, Morar, and Knoydart may be in part controlled by the closest of these encircling features, while another, with greater radius, cuts through Sguman Ceinntich.

(*g*) Three arcuate fractures swing off from the Great Glen fault towards the western isles, joining up with the radial system from the hypothetical Eigg centre.

(*h*) Fractures radiate from a centre in the Cairngorm mountains.

The impression gained from this complex disposition is that a system of Tertiary fractures has been grafted upon the original late Caledonian grain, which had been dominated by the Great Glen fault. Where previous fractures, dating from the late Caledonian block movements, were either so distant from the Tertiary centres, or so little divergent in orientation as to act as avenues of relief to the particular stress directions involved in the subsequent Tertiary vulcanism, no new fracturing ensued, and relief occurred along pre-existing planes of weakness. Further west, nearer the Tertiary vulcanism, and in areas where considerable divergence existed between the orientation of the Caledonian fractures and the later Tertiary stress directions, strains would develop along new directions oblique to those of Caledonian age. There evidently resulted a superposition of new strains on old ones, and the formation of a criss-cross pattern of ancient and more modern fractures.

Two questions immediately come to mind. Firstly, there are four plutonic centres between Skye and Mull, and three of these occur in one line. Indeed, the centres of Rhum, Ardnamurchan, Mull,

and Arran all lie on a single N.N.W.–S.S.E. line, though with a spacing that does not appear to follow any simple mathematical progression. Yet the radial fractures postulated from the topography diverge from a single apparent centre near Eigg, where only volcanic rocks are exposed. Further, this apparent centre is slightly removed from Rhum, which is the only plutonic mass near to the area of convergence. If there were any significance in the converging pattern of fractures it might be expected that each plutonic centre would have had its own individual system extending into the mainland. This does not appear to be so.

Secondly, although the dyke swarms, which indicate post-lava and post-plutonic tension, are locally radial, in general they cut right across the region, preserving over wide areas a N.W.–S.E. direction. When the main swarm developed it must be assumed that a single major direction of strain relief existed in the crust, with a complete disregard to former directions of fracture. Consequently, assuming the radial pattern of Tertiary fractures to have validity, it is of a different category to those up which the magma welled up to form the dyke swarms at the close of the igneous cycle.

With regard to the first point, it is possible that not all the plutonic centres have been exposed, and that another sunken centre, concealed below lava and the sea, may also exist. Further, those that are exposed need not necessarily have been strictly contemporaneous. A centre near Eigg may have been the first to form and, in so doing, would have involved the adjacent crust in radial and peripheral fractures which possibly eased the strain for the subsequent development of centres in Skye, Ardnamurchan, Mull, and Arran.

Coming to the second point, the fractures of the dyke swarms may not have been contemporaneous with those with which this discussion is mainly concerned. It was seen that the shear fractures in the Konkan and Gujarat in India, occur in a single dominant direction and were later than the complex triangular fractures of the dyke clusters. In Scotland, on the other hand, the dykes follow a relatively simple pattern, mainly N.W.–S.E. except for the radial dykes locally connected with Skye, Rhum, and Arran, whereas the postulated fractures form a complex pattern, both radial and peripheral. Indeed, these Scottish fractures somewhat resemble the arrangement of dykes on the east side of the Junagadh pluton in Saurashtra (Auden, 1949, p. 131). The two roles were possibly thus reversed. The question whether or not any particular set of fractures became the avenue of upwelling of magma would have depended on the degree of their opening during formation under stress couples, as well as on the depth and availability of magma, and the magmo-piestic level, at the different times of crustal dislocation (1949, p. 149).

The matter may be considered further. The straight line joining the Rhum, Ardnamurchan, Mull, and Arran centres runs N.N.W.–S.S.E., which is oblique to the dominant N.W.–S.W. direction of the main Mull swarm. While a line of weakness extended during the primitive caldera period for 103 miles, between the Rhum and Arran Centres, by the time that most of the dyke-magma of the swarms was intruded a new set of fractures oblique to the original co-central line had developed. The extension of the caldera centres to Skye, and to Mourne, Carlingford, and Slieve Gullion, in Ireland, further emphasizes the obliquity of the co-central line of plutons to the direction of the dyke swarms. Moreover, the pronounced radial dykes of Rhum, as well as the slightly more subdued radial pattern of Skye and Arran, indicate that each centre had its local peculiarities. It is not so anomalous therefore to suppose that the crustal fractures, unaccompanied by dyke intrusion, which are the main subject of this present discussion, should have converged to one centre, since that centre may have been the first focus of Tertiary volcanic activity, and would have developed under maximum crustal strain. It is perhaps significant that the greatest concentration of fractures has occurred surrounding the area where the exposed plutonic centres are closest together.

Some connection probably exists between the spacing of the topographical features, which have been interpreted as faults or shatters, and the thickness of the crust involved in the block dislocations. A considerable number of the larger fjords and valleys are 11–14 miles apart, averaging about 12½ miles or 20 km. The postulated fractures of Sutherland and Ross are on an average about 3½ miles apart, while the major fractures of the Great Glen system are in general separated by distances of either 6–8 miles or 13–14 miles. It may not be too fanciful to see in these distances a series 3½–6/8–13/14 which represent simple fractions and multiples of the crustal thickness undergoing stress. In Gujarat the major shears occur at the intervals of 2½–4 miles (Auden, 1951, p. 145), and this, too, is thought to have significance in relation to crustal thickness.

Whether or not the closer spacing of the Sutherland fractures is due to their predominance in the foreland of the Caledonian orogency, while the Great Glen system of mid-Devonian faulting is located within the orogenic belt of overfolded and duplicated formations, and greater crustal thickness, can only be hazarded. In the long interval between the mid-Devonian and the Tertiary, the orogenically exaggerated pile of Caledonian metamorphic formations, with roots extending down into the asthenosphere, was probably reduced by subcrustal creep and other readjustments. By the Tertiary era, the crust throughout the Caledonian orogenic zone would, indeed, have been

more or less grafted on and equalized to the Archaean crust of the original foreland, even though each of the once strongly differentiated segments still preserved their former characteristic grain. During the early Tertiary vulcanism little difference probably existed, as far as thickness of crust was concerned, in physical reactions to stress between the ancient foreland and the less ancient, but still old, Caledonian orogenic belt. The whole crust surrounding the calderas and plutonic centres doubtless reacted as one unit, with similar strain reactions as regards thickness, although with different grain directions that probably in part influenced the directions of faulting and shattering. Nevertheless, during the time of formation of the Great Glen fault system, the crust throughout the Caledonian orogen was no doubt thicker, through tectonic accretions, and the spacing of the faults now preserved remains a witness to conditions which then existed, but now no longer obtain.

V. Analogies with Norway, Africa, and India

Norway.—Finally, it may be suggested that parts of Norway are involved in an analogous system of fractures. A rhombic pattern of presumed fractures is present in the gneisses 35 miles south-east of Stavanger, as well as far to the north, in the Lofot gneisses of South-Western Hinnoey, near latitude 68° 23′ N. and between Greenwich east longitudes 15° and 15° 45′. A very conspicuous north–south feature 28 miles in length is evident from north of Afjord southwards to Skarsaunet, within 15 miles of Trondheim. This cuts across the strike of all the formations. N.N.W.–S.S.E. faults are presumably responsible for the passages between the different islands W.S.W. of Trondheim, between Tustna and Kirksetereora. Finally, it is possible that an arcuate fracture over 50 miles in length extends from near Skeivik (66° 28′ N.: 13° 18′ E.) in the Melfjord, north-eastwards to Groetae and Graetaenes. This cuts across the contact between the Cambro-silurian and the Fjaelgranite, and has a radius of about 60 miles.

Norway lacks the complication of the Tertiary plutonic centres, and the dislocations suspected there may be regarded as equivalent to those in the Scottish Highlands, before modification by the stresses arising from the calderas and intrusion of plutonic masses.

Africa.—A study of the striking rift system of Africa is clearly relevant to a discussion of faults associated with recent vulcanism, but this would involve considerations beyond the scope of the present paper. It suffices to notice the following principal features:—

(1) The arcuate disposition of *échelon* faults belonging to the Lake Tanganyika system, and their radial distance of 600 miles from a centre close to Mount Kilimanjaro.

(2) The system of faults running parallel to the Somaliland–Kenya coastline, and Eastern Madagascar.

(3) The north–south system of faults represented by Lakes Rudolf and Natron, and the western side of Lake Victoria.

The complexity in detail in any one area of the Rift system is seen in the fine geological map on the scale of 1 : 500,000 of the Lake Kivu area (2° S.: 29° E.) produced by Salée, Boutakoff, and Poussin in 1939. Consideration of only a limited area tends indeed to obscure the regional relationships, and the broader pattern only emerges when a larger area is viewed, as for example, in the map on page 24 of their Memoir.

India.—One further point may be stressed. Both the Scottish Highlands and the Himalaya are regions of thrust tectonics. It might therefore be thought that, because the Dalradian and Moine Zones of overthrusts and recumbent folds are also broken up by late-Caledonian and Tertiary fractures, a similar development of fractures should be present in the Himalaya. It is true that shatter zones do exist in the Himalaya, such as that discussed in the previous paper at the Marora dam site, Further, tear faults of considerable magnitude are known cutting the outermost of the Siwalik ranges in the Hardwar gap of the Ganga (Ganges) and the Koch gap of the Yamuna (Jumna) rivers. But there is nothing in the Himalayan ranges, so far as my observations go, that is comparable to the regional control of the drainage by fractures observed in Scotland. The river system of the Himalaya follows a dendritic pattern which was developed from large consequent drainage channels that arose while the tectonic accretions in the crust emerged in primitive plateau form in response to isostasy. It would be an exaggeration to claim that the Himalayan drainage pattern is entirely independent of geological grain and fractures, but in many regions this is almost so.

The reason for this difference is that the Highlands represent an old stabilized crust that was cut up by major vertical fractures only after the Caledonian orogeny had subsided, and again, long subsequently, by Tertiary faulting and shattering. The Himalaya, on the other hand, are tectonically very young, with great thrust movements and upheavals even of Pleistocene age. The time has not yet arrived for a new type of tectonics to develop, such as happened when the Middle-Old-Red-Sandstone block faulting and Tertiary vulcanism were superimposed on the Caledonian structures. Indeed, in so far as the Tertiary fractures are concerned, the analogy which should be drawn with Scotland is not the Alpo–Himalayan system, but the region of the Deccan Plateau, Konkan, and Gujarat, where fracturing of the Deccan lavas was possibly contemporaneous with that of the basalts of the

FIG. 1.—LEAD VEIN ALONG SHATTER ZONE, BELLSGROVE.

FIG. 2.—SHEET JOINTING, SHORE OF LOCH SUNART.

western isles. In both areas, however, there must have been teletectonic connection with the Alpo–Himalayan orogeny.

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SUDAN GEOLOGICAL SURVEY,
P.O. BOX 410,
KHARTOUM.

EXPLANATION OF PLATE VIII

FIG. 1.—Lead vein along shatter zone, Resipol, Bellsgrove, Strontian. View looking west. Grid coordinates: 1830 : 7660.

FIG. 2.—Sheet jointing parallel to W.N.W.–E.S.E. Tertiary basalt dyke, shore of Loch Sunart. Grid coordinates: 1715 : 7640.

Magnetic Correlation in Volcanic Districts

By J. Hospers

Abstract

Alternating zones of normal and reverse natural permanent magnetization, each comprising about twenty-five flows, have been found in the Tertiary and Quaternary plateau basalt series of Iceland. The techniques for measuring this permanent magnetization are discussed and some results shown. It is suggested that zones of normal and reverse magnetization may be useful for correlation purposes in volcanic districts. Some other possible applications of rock magnetism are mentioned.

I. Introduction

LAVA flows, as well as other igneous rocks, possess natural permanent magnetization. Investigations have established that this permanent magnetization was acquired, as a rule, when the flows cooled down in the local geomagnetic field after extrusion and solidification. In Table I some representative values of the intensity of the natural permanent magnetization of lava flows are shown.

Table I.—Mean Intensity of the Natural Permanent Magnetization of Lava Flows

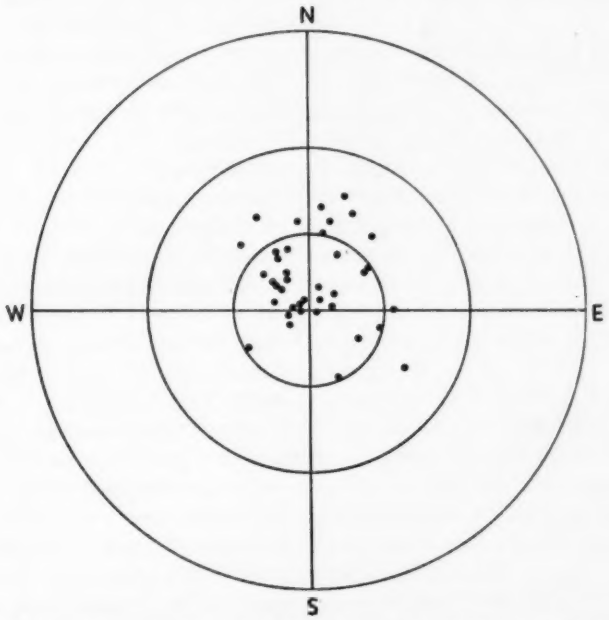
Group	Country	Mean intensity (in gauss)
Historic flows	Iceland	$13{\cdot}9 \times 10^{-3}$
Postglacial flows	,,	$11{\cdot}9 \times$
Late Pleistocene flows . . .	,,	$6{\cdot}3 \times$
Early Quaternary flows . . .	,,	$5{\cdot}0 \times$
Late Pliocene flows	,,	$3{\cdot}9 \times$
Miocene flows	,,	$3{\cdot}6 \times$
Miocene and Pliocene flows [1] . .	France	$3{\cdot}6 \times$
Eocene flows [2]	Northern Ireland	$1{\cdot}7 \times$

The natural permanent magnetization of lava flows younger than Early Quaternary is always approximately in the direction of the present geomagnetic field. This means that in western Europe and Iceland the north-seeking pole of the permanent magnetization points towards the north and downwards. However, Early Quaternary and older lava flows are often found to possess reverse magnetization, i.e. permanent magnetization directed approximately opposite to the present geomagnetic field. In sections in Tertiary plateau basalts, as found for example in Iceland, it appears that flows with normal and reverse magnetization are grouped in alternating zones, each comprising twenty-five flows on the average. There are no statistically

[1] From Roche, 1950, 1951, 1953.
[2] From Hospers and Charlesworth, 1954.

significant differences between the mean intensities of normal and reverse magnetization in the same series of flows. This is the reason why the mean intensities of normal and reverse magnetization have not been shown separately for the Early Quaternary and older lava flows in Table I.

In Text-fig. 1 the directions of the natural permanent magnetization of a number of samples from Icelandic Tertiary lava flows with normal magnetization are shown on a stereographic projection. It will be seen

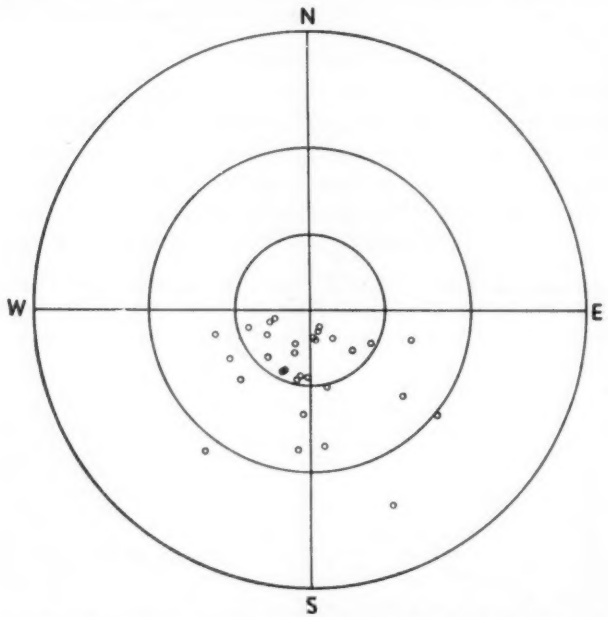


TEXT-FIG. 1.—Stereographic projection (lower hemisphere), showing the directions of the natural permanent magnetization of oriented samples from Icelandic Tertiary lava flows with normal magnetization. Only one sample was taken from each flow.

from this figure that, even though all samples are from different flows, the scatter is still small and very far from being random. A similar picture is presented by Text-fig. 2. This figure shows the directions of the natural permanent magnetization of samples from Icelandic Tertiary lava flows with reverse magnetization. These two figures show that there need not be any doubt whether a specimen has normal or reverse magnetization, even if only the vertical component is measured.

The normal permanent magnetization is now generally thought to have been acquired when the lava flow cooled down in the earth's magnetic field after extrusion and solidification. The reverse permanent

magnetization, in the present author's opinion, has been acquired under similar conditions but in a reversed geomagnetic field, due to a complete reversal of the earth's magnetization. The grounds for this statement have been amply set forth in an earlier paper (Hospers, 1953–4). However, for our purpose it is not really relevant whether or not this interpretation is correct. What matters is that zones of normal and reverse magnetization, each comprising about twenty-five flows, alternate in series of plateau basalts. These zones of normal and



TEXT-FIG. 2.—Stereographic projection (upper hemisphere), showing the directions of the natural permanent magnetization of oriented samples from Icelandic Tertiary lava flows with reverse magnetization. Only one sample was taken from each flow.

reverse magnetization may form a useful tool for correlating sections in a series of plateau basalts, which by any other means is often extremely difficult.

II. MEASUREMENTS

For purposes of correlation it will generally be sufficient to determine only the direction of the vertical component of magnetization. If the intensity of the permanent magnetization of the flows is sufficiently large, it is often possible to find the direction of the vertical component of magnetization by holding a compass near the top and bottom

of an exposed flow. The susceptibility of basic lava flows is about 10^{-3}; the magnetization induced in the earth's present field, which has a strength of approximately 0·5 gauss, is therefore about $0{\cdot}5 \times 10^{-3}$ gauss. The natural permanent magnetization is several times larger (cf. Table I), the net intensity of magnetization of reversely magnetized flows is therefore only slightly less than the intensity of the permanent reverse magnetization. The north-seeking pole of a compass needle will be repelled near the top and attracted near the bottom of a reversely magnetized flow. For flows with normal magnetization the compass needle will show the reverse behaviour.

Another method is to collect at least two specimens (with top and bottom marked) from each flow and to measure the direction of the vertical component with a good compass or, for greater sensitivity, with a vertical magnetometer. A roughly isometric sample of about 10 cm. diameter is held near one of the poles of the magnet and the specimen turned over in order to eliminate the effect of the induced magnetization. The direction of the deflection of the magnet is noted and gives the direction of magnetization of the specimen. A vertical magnetometer can easily detect intensities of about 3×10^{-3} gauss in such samples. Using a compass this method has independently been applied by Rutten and den Boer (1954) for the correlation of Tertiary and Quaternary igneous rocks in France.

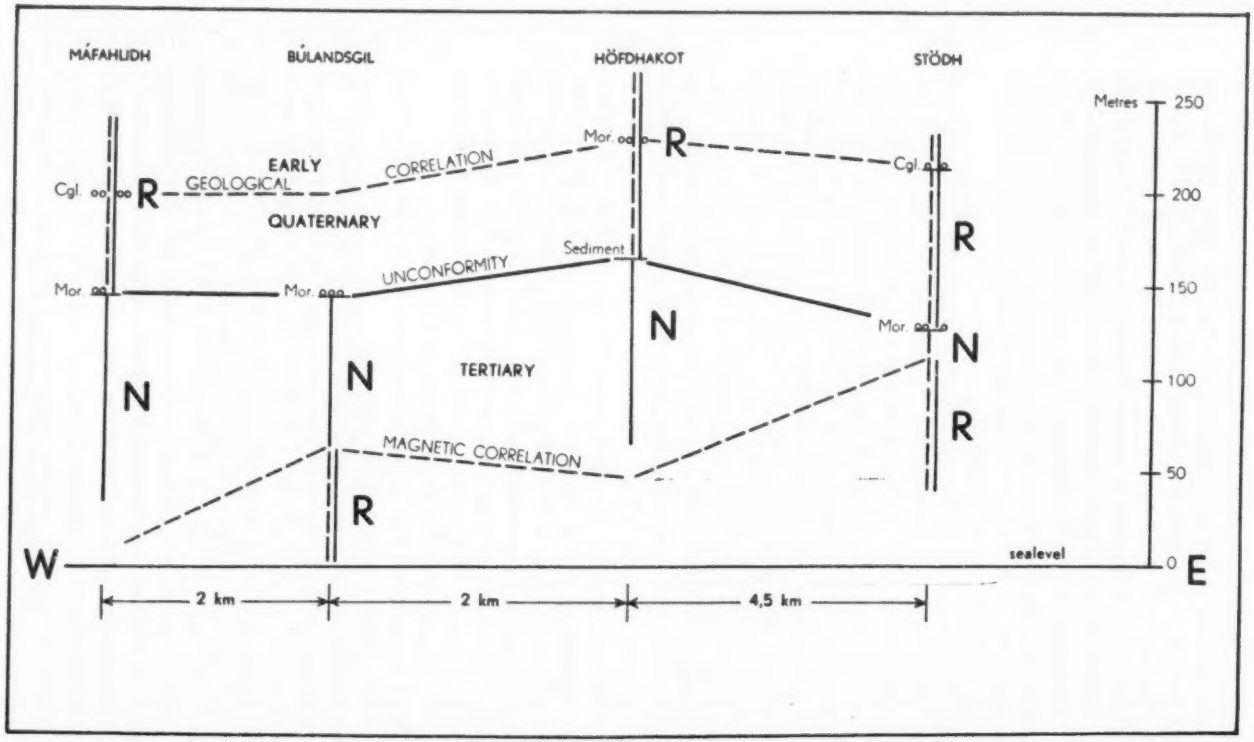
For smaller intensities or more accurate measurements a simple astatic magnetometer may be used. It consists in principle of two parallel and equal magnets (pointing in opposite directions) connected by a rigid holder and suspended on a fibre. When oriented cylindrical or cubical specimens are cut, the same instrument may be used to determine all three components of the permanent magnetization, as well as its intensity and the susceptibility of the rock.

By these methods an adequate picture of the distribution of normal and reverse magnetization may be obtained.

Occasionally samples may be found which yield a direction of magnetization not in agreement with the magnetization of the flows above or below. In that case the rest of the similarly magnetized series may have been removed by erosion; it is then advisable to look for indications of an unconformity in the succession (cf. Text-fig. 3, the section of Mt. Stödh). Also, it is conceivable that lightning, intrusion in the immediate neighbourhood, faulting, deep burial, or magnetic instability of the rock may have changed the magnetization, acquired after extrusion and solidification of the flow. The first two are known to have occurred.

III. Discussion of Some Results

Text-figs. 3–4 show some results obtained in Iceland. They are



TEXT-FIG. 3.—Early Quaternary and Tertiary plateau basalts exposed on the north coast of Snaefellsnes, western Iceland. The Early Quaternary flows are reversely magnetized (R). The Tertiary series shows a normally magnetized zone at the top (N) which is only represented by one flow in the Stödh section, and a reversely magnetized zone (R) at the bottom. The unconformity between the Tertiary and Early Quaternary series was established on geological grounds only. The total number of measured flows in all four sections taken together is sixty-five.

not meant as a demonstration that correlation by using the natural magnetization of the plateau basalts has been achieved, they merely serve the purpose of showing what kind of information is obtained by this method.

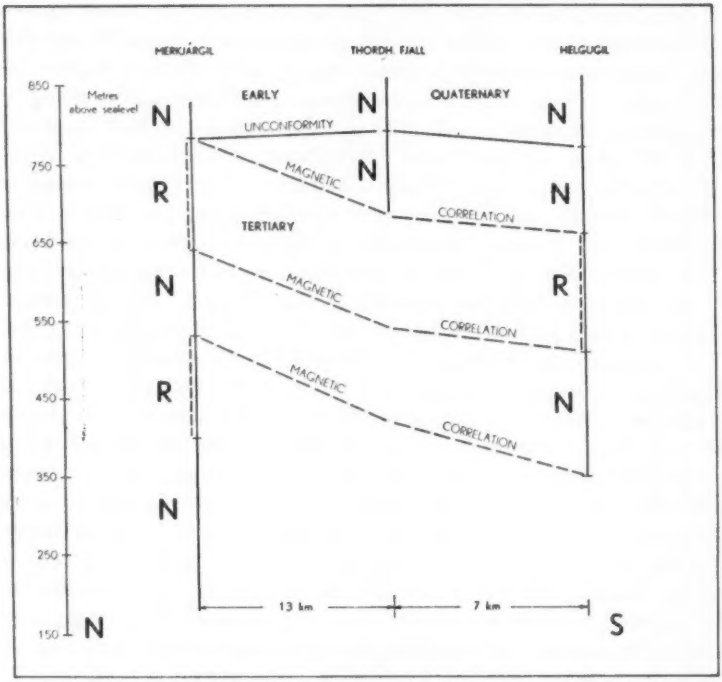
In Text-fig. 3 a number of sections in Early Quaternary and Tertiary plateau basalts from western Iceland are shown. The flat-lying Early Quaternary series is reversely magnetized throughout; it rests unconformably on gently dipping Tertiary plateau basalts. It will be seen that the zone of normal magnetization at the top of the Tertiary series is cut off towards the east by the unconformity. An Early Quaternary age is assigned to the upper series as it contains glacial beds and sediments with an Arctic mollusc fauna (cf. Pjetursson, 1910, Áskelsson, 1938). The reversely magnetized Early Quaternary zone can be traced in western Iceland as far as geological correlation permits, that is, over a distance of 125 km. Conversely, it might be possible to trace the Early Quaternary series by following this reversely magnetized zone.

Text-fig. 4 shows three sections in the Tertiary and Quaternary plateau basalts between Akureyri and Mývatn, in northern Iceland. The Tertiary series is unconformably overlain by a series of approximately six lava flows, containing a glacial bed. This upper series is therefore indicated as Early Quaternary, but this should not be taken to mean that it is exactly equivalent with the Early Quaternary series of western Iceland. Text-fig. 4 shows that alternating zones of normal and reverse magnetization are found. The magnetic correlation lines were drawn as shown because the available geological evidence makes this the most likely solution. The magnetic information alone cannot decide which of the two R zones in the Merkjárgil section should be correlated with the R zone in the Helgugil section. This figure demonstrates the necessity of sampling closely spaced sections and also of using all available additional geological information.

IV. Other Applications and Methods

For more detailed correlation, that is, correlation of individual flows, accurate measurements on a fairly large number of samples from the same flow may be useful. If carefully oriented specimens are subjected to an accurate determination of the direction of natural permanent magnetization, the true direction of magnetization of the flow (corresponding to the direction of the local geomagnetic field in which it cooled down) can be determined within narrow limits. For example, from a Tertiary (Eocene) lava flow in Northern Ireland four oriented samples were taken at intervals of 4 feet and two cylindrical specimens cut from each sample. The calculated mean direction of magnetization of this (reversely magnetized) flow has a declination of N. 192° E. and an inclination of − 68°. The probability is 50 per cent

that the true direction of magnetization of this flow will deviate by more than 2·9° from the calculated mean direction; for a probability of only 5 per cent this angle becomes 7·3° (Hospers and Charlesworth, 1954). This result is found by using Fisher's (1953) statistical treatment of dispersion on a sphere. As the earth's magnetic field at a given



TEXT-FIG. 4.—Early Quaternary and Tertiary plateau basalts, exposed in northern Iceland. The unconformity was established on geological grounds only. The magnetic information had to be supplemented with some geological information in order to determine the most probable correlation. The total number of measured flows in all three sections taken together is eighty-three.

locality suffers considerable changes in direction and strength (the " secular variation "), it may be possible to characterize each flow by its direction of magnetization and thus to carry out a correlation of individual flows. In this type of work a thorough statistical analysis of the results may be necessary, for which Fisher's (1953) method should be used.

Chevallier (1925) was presumably the first who dated recent flows by rock magnetism; in recent years van Bemmelen (1949, p. 297) has

again drawn attention to the possibility of using the secular variation of the geomagnetic field as a means of dating recent lava flows.

Normal and reverse magnetization are also found in dykes and other intrusive bodies. In fact, the first carefully investigated instance of reverse natural magnetization is that of the northern England dykes (Bruckshaw and Robertson, 1949). The direction of magnetization of intrusive rocks might therefore be of some use to distinguish between dykes or other intrusive rocks of different ages. There are indications that this is possible (cf. Bruckshaw, 1953).

Where series of plateau basalts are exposed on accessible valley sides it may be possible to determine the position of the boundaries between zones of normal and reverse magnetization by means of vertical magnetic force field surveys. Changes of 1,000 gammas or more in the vertical magnetic force are expected near these boundaries.

Finally, the present author would like to draw attention to the fact that the mean intensity of the natural permanent magnetization of lava flows (Table I) decreases with increasing age. This mean intensity might, in special cases, serve as a useful additional criterion of age (cf. Koenigsberger, 1936). It should be kept in mind, however, that the present intensity of magnetization of an igneous rock does not depend on age alone; it also depends on the initial intensity, acquired after extrusion and solidification. This initial intensity is a function of the strength of the local geomagnetic field, the percentage of ferromagnetic minerals present and the grain size of these minerals. The figures for the mean intensities of the historic and postglacial lava flows of Iceland, given in Table I, should be left out of consideration in this connection. For these groups the samples were taken from the tops of the flows, whereas the samples of the other groups were taken from their exposed central parts. As the intensity of the top part exceeds that of the central part of a given lava flow by a factor $1\frac{1}{2}$–2, the figures quoted for the historic and postglacial flows in Table I are too large by a factor $1\frac{1}{2}$–2 when compared with the other groups.

V. Acknowledgments

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New Genera of Carboniferous Tetracorals from Western Canada

By PATRICK K. SUTHERLAND

(PLATES IX AND X)

ABSTRACT

Four new solitary tetracoral genera and their type species from the Mississippian of Western Canada are described, named, and discussed. These new genera are part of several previously undescribed coral faunas from the northern Canadian Rocky Mountains.

INTRODUCTION

SEVERAL new genera and species of tetracorals have been recognized during an investigation of a large and varied collection of Carboniferous fossils from the northern part of the Canadian Rocky Mountains and the southern part of the Mackenzie Mountains. A detailed description of the tetracorals from these collections forms part of a general regional report on the Carboniferous stratigraphy exposed in north-east British Columbia. This report is being published as a Bulletin of the Geological Survey of Canada, but four of the new coral genera and their type species are here described in advance. The new genus *Kakwiphyllum* has been recognized by the author in Geological Survey of Canada collections from widely scattered areas ranging from the southern Canadian Rocky Mountains in Alberta to the Liard River region in the North-west Territories. It seems likely that it will appear again in future collecting in the Rocky Mountains. The new genus *Liardiphyllum* is a curiosity unlike any Carboniferous coral known to the author.

A description of other new species, a full discussion of family and generic affinities, a description of the Carboniferous stratigraphy and a comprehensive bibliography are not given here, but will be found in the forthcoming Bulletin already mentioned.

All figured specimens are deposited in the collections of the Geological Survey of Canada, Ottawa. I am indebted to the Geological Survey of Canada for permission to publish here a description of these genera. This investigation was mainly carried out in the Sedgwick Museum, Cambridge and I would like to thank Dr. O. M. B. Bulman for the kind help and advice he has given me in this work.

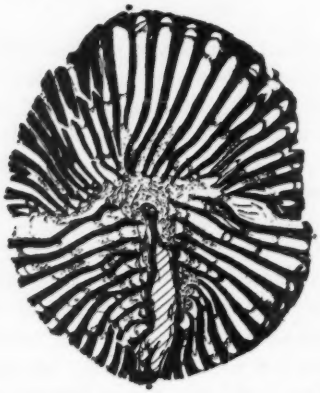
Family ZAPHRENTOIDIDAE

CANADIPHYLLUM gen. nov.

Type Species.—Canadiphyllum knoxi sp. nov. (Pl. IX, figs. 1–2). Middle Mississippian, Western Canada.

Generic Characters.—Simple trochoid corals in which the major septa of the cardinal quadrant are pinnate and often almost at right angles to a prominent cardinal fossula ; the septa of the counter quadrant have a subparallel to radial arrangement ; minor septa short or absent ; tabulae numerous and no dissepiments present.

Remarks.—*Canadiphyllum* resembles the Middle Devonian genera *Aulacophyllum* Edwards and Haime, 1850 and *Pinnatophyllum* Grabau, 1922 (a junior synonym of *Aulacophyllum* according to Stumm, 1949, p. 16), in the pinnate arrangement of the major septa of the cardinal quadrant along the cardinal fossula, but differs from those genera in



TEXT-FIG. 1.—*Canadiphyllum knoxi*, sp. nov. Holotype, G.S.C. 10566; transverse section, late ephebic stage. × 3 (enlarged drawing of Pl. IX, Text-fig. 1*a*).

having no dissepiments and in being of much simpler construction with fewer septa. Also, *Pinnatophyllum* is said to have (according to Grabau in Bassett, 1935, p. 444) no true tabulae except in specialized forms.

A somewhat similar pinnate arrangement of the major septa occurs in the Carboniferous genus *Cystophrentis* Yu (1931, p. 18) from the Lower Fengninian of China (equal to Tournaisian of Europe and Lower Mississippian of North America), but this genus has a lonsdaleoid dissepimentarium in the ephebic stage.

Canadiphyllum knoxi sp. nov.

Pl. IX, figs. 1a-f, 2a-c ; Text-fig. 1.

Diagnosis.—Small almost straight trochoid *Canadiphyllum* with approximately 50 to 52 major septa in the ephebic stage, of which those in the counter quadrants tend to a subparallel arrangement ; counter septum usually somewhat shortened ; septa composed of fibre fascicles not grouped into trabeculae ; no minor septa present ; tabulae

numerous, close together, periaxially arched and depressed into cardinal fossulae ; dissepiments absent.

Description.— All specimens studied had been somewhat water-worn before final deposition and the exterior of the epitheca is not well preserved but it appears to have been nearly smooth. The corallites are almost straight and any slight curvature which is present does not appear to be in a constant plane. The calyx is deep and slopes into a deep depression in the cardinal fossula. The diameter of the holotype at the base of the calyx is 16mm. and the original length is estimated to have been 22 to 25mm.

There are 48 to 52 long major septa present in the ephebic stage which do not meet axially. Minor septa are absent. The septa of the cardinal quadrants vary from a marked pinnate to an almost right-angled arrangement along the cardinal fossula which extends to the axis. The cardinal septum is short from an early stage. The major septa of the counter quadrants vary from a radial to a sub-parallel arrangement giving a marked angle between them and the alar septa. What appears to be an inner wall around the cardinal fossula is seen in transverse section in some specimens (Pl. IX, fig. 2a, Text-fig. 1), but this feature is caused by the intersection of crowded and thickened tabulae where they bend downward at the edge of the cardinal fossula. The major septa do not reach beyond this area. The counter septum is slightly shortened.

Numerous incomplete, closely-spaced tabulae rise gradually from the periphery and are slightly domed periaxially before turning steeply downward at the edge of the cardinal fossula. Dissepiments are absent.

Septal Structure.—The septa in the type species are composed of fibrous tissue (as described by Wang, 1950, p. 183) in which the fibre fascicles are perpendicular to the septal plane and are not grouped into trabeculae.

Holotype.—G.S.C. coll. no. 10566.

Occurence.—G.S.C. loc. no. 16038, Middle Mississippian, Halfway River Valley, north-east British Columbia ; in a new formational unit made up of interbedded thin chert and limestone layers ; in a light grey coarsely crystalline, crinoidal limestone layer, 95 feet below the highest exposed beds on an unnamed mountian immediately north of the Halfway River, 35 miles west of the Alaska Highway.

Family CANINIIDAE

ZAPHRIPHYLLUM gen. nov.

Type Species.—Zaphriphyllum disseptum sp. nov. (Pl. IX, figs. 3a-f). Mississippian, Western Canada.

Generic Characters.—Solitary trochoid corals which have numerous long major septa which tend toward a radial symmetry ; a prominent

well-developed cardinal fossula ; tabulae arched periaxially and down-turned into the fossula ; well developed dissepimentarium, at least in ephebic stage.

Remarks.—Like typical members of the family Zaphrentoididae, the type species of *Zaphriphyllum* is small, trochoid in shape, has long major septa and a prominent cardinal fossula. On the other hand, it resembles members of the family Caniniidae in having a prominent ring of dissepiments in the ephebic stage. It is tentatively referred to the Caniniidae until its relations are better understood. *Zaphriphyllum* differs from *Caninia* Michelin (sensu stricto) in possessing a trochoid shape, long major septa and a much more highly developed cardinal fossula.

Zaphriphyllum disseptum sp. nov.

Pl. IX, figs. 3a-f.

Diagnosis.—Small to meduim sized, curved, trochoid *Zaphriphyllum* with 42 to 46 major septa in the ephebic stage which tend to a radial symmetry ; dissepimentarium and minor septa occupy about one-fifth of radius in ephebic stage ; prominent, usually open cardinal fossula located on the convex side of the corallum ; tabulae mostly incomplete and arched, but down-turned steeply in axial region around cardinal fossula ; septa composed of fibre fascicles not grouped into trabeculae.

Description.—The specimens studied are small, moderately curved and trochoid. The surface of the epitheca shows fine interseptal ridges and irregularly spaced, rather pronounced, transverse rugae. The nature of the calyx is unknown. The holotype is about 30 mm. long without calyx. The total length is estimated to have been 45 to 50 mm., and the relation of diameter to number of major septa is as follows :—

Diameter—21 mm.	: 45	major septa	(base of calyx)
„ 15·5 mm.	: 40	„	„
„ 12 mm.	: 34–36	„	„

The major septa are long and approximately straight but the axial ends may be curved and twisted individually. The septa extend to the edge of the cardinal fossula in the early stages but are slightly withdrawn in the ephebic stage leaving a prominent open fossula. The cardinal fossula extends beyond the axis and is up to three-fifths the diameter in length. It is marked by the downturning of the tabulae at its edge. It has parallel sides, but it may expand in the axial region in the late ephebic stage. (Pl. IX, fig, 3a), Alar septa are obscured in the ephebic stage by the tendency of the major septa to radial symmetry. The major septa are dilated in the tabularium in the early ephebic stage, but tend to be only slightly thickened or thin

throughout their length in the adult form. Minor septa are present and their length is about one-fifth to one-sixth of the radius in the ephebic stage. The dissepimentarium is correspondingly wide and made up of small dissepiments concentrically arranged between the septa.

There are numerous complete and incomplete tabulae which are moderately domed and downturned at their periphery but are deflected almost vertically into the cardinal fossula, thus giving a distinct siphonofossula. In the axial region there are occasional small patches of irregular tissue present between the tabulae (Pl. IX, fig, 3e), the function of which is unknown. There are two to three rows of small somewhat irregular and almost vertically inclined dissepiments.

Septal Structure.—The type specimens have fibro-lamellar skeletons in which the fibre fascicles are not grouped into trabeculae and are perpendicular to the septal plane.

Holotype.—G.S.C. coll. no. 10568.

Occurrence.—G.S.C. loc. no. 16622, Liard Range, North-west Territories; 18 miles north of Fort Liard on west slope of small mountain, about two miles west of Big Island in the Liard River, in the lower limestone series (as described by Hage, 1945), in interbedded shale and limestone, about 80 feet below cherty limestone.

The formations in this region have not as yet been named or described in detail but the associated fauna suggests a Middle Mississippian age for the forms just described.

KAKWIPHYLLUM gen. nov.

Type Species.—*Kakwiphyllum dux* sp. nov. (Pl. X, figs. la-c) Mississippian, Western Canada.

Generic Characters.—Large, solitary, cylindrical corals with long major septa which extend to axial region, but do not join; major septa have overall radial symmetry which may be modified by regular or irregular grouping of septa into bunches caused by shortening of septa in some areas; cardinal and counter septa and the cardinal fossula may tend to be obscured in ephebic stages by radial arrangement of septa; minor septa short or absent; peripheral zone of dissepiments consisting of an outer series of lonsdaleoid dissepiments through which the septa are not continuous and an inner zone in which dissepiments are small and have a herring-bone or concentric arrangement between septa; dissepiments often gradational with the tabulae which are numerous, incomplete and inclined downward axially where they form a concave floor.

Remarks.—The genus *Kakwiphyllum* differs from *Pseudozaphrentoides* Stuckenberg, 1904, in having a pronounced zone of lonsdaleoid dissepiments. It also differs from that genus and from *Siphonophyllia*

Scouler in having incomplete tabulae which are inclined downward in the axial region and form a concave floor which is not particularly associated with the cardinal fossula but covers the entire axial region. *Kakwiphyllum* also differs, in the axial depression of its tabulae, from the genus *Keyserlingophyllum* Stuckenberg, 1895, which is characterized by four pronounced fossulae which are related to the cardinal, counter and two alar septa.

The genus *Kakwiphyllum* is provisionally referred to the family Caniniidae until its relations are better understood. It differs from typical members of this family in the axial depression of the tabulae.

Range and Distribution.—Forms belonging to the new genus *Kakwiphyllum* have been recognized from three widely separated areas in the Canadian Rocky Mountains. (1) Specimens of a new species, not here described but in the G.S.C. collections, from a locality near Banff, Alberta, occur at a horizon apparently near the base of the Rundle formation and in association with *Lithostrotion* cf. *pauciradiale* (McCoy). (2) The genoholotype, described below, was collected in the Kakwa-Jarvis Lakes region of British Columbia, 275 miles northwest of Banff, and is believed to be from the upper part of the Rundle formation (see *Remarks* under species description). (3) *Kakwiphyllum* cf. *dux* (Pl. X, figs, 2a-c), from limestones of definite Mississippian age, occurs in the Liard River area of the North-west Territories 500 miles north of the Kakwa-Jarvis Lakes region and in association with a large phaceloid species of *Lithostrotionella* (*Thysanophyllum*). A middle to upper Mississippian age is suggested for the genus by the known range from the base to near the top of the Rundle Formation.

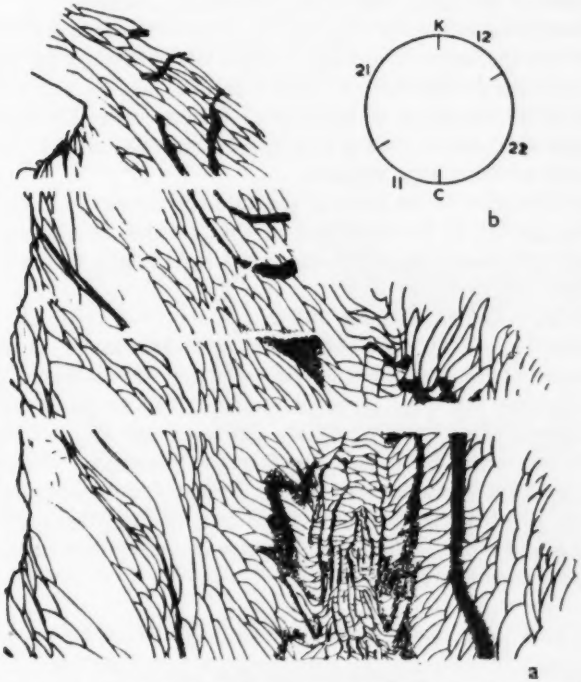
Kakwiphyllum dux sp. nov.

Pl. X, figs. la-c, Text-figs. 2a-b.

Description of holotype.—The holotype consists of a broken and partly weathered fragment of a large solitary cylindrical coral. The epitheca has rounded interseptal ridges and there are very fine transverse growth lines on top of large wrinkles and constrictions, caused by marked periods of rejuvenation, giving the surface an irregular appearance. The nature of the calyx is unknown.

In the late neanic stage the septa became dilated at the inner edge of the dissepimental zone. This feature almost disappears in the ephebic stage when the major septa are only very slightly thickened in the tabularium. There is no variation in thickness of the septa in different quadrants. There are 66 long major septa present in the ephebic stage at a diameter of 64 to 66 mm. They have an overall radial symmetry but are grouped into four series by areas of shortening and bunching of the septa. Two of these regions of shortening correspond to the cardinal and counter septa but the other two, which are almost oppo-

site to each other, are at variance with the bilaterial symmetry about the cardinal-counter line (Text-fig, 2b, Pl. X, fig. 1b). It is doubtful if this feature is constant within the species (See *Remarks* below). No cardinal or counter fossulae are developed in the holotype and alar septa cannot be detected. Minor septa are absent but there are low, rounded, septal grooves on the exterior of the epethica which would correspond to minor septa.



TEXT-FIG. 2.—*Kakwiphyllum dux* sp. nov. Holotype, G.S.C. 10569; (*a*) longitudinal section at right angles to cardinal-counter line, × 1½; (*b*) diagram of Pl. X, Text-fig. 1*b*, to show relation of cardinal and counter septa to grouping of septa. Figures refer to number of septa between each area where septa are shortened.

In the ephebic stage the pronounced dissepimentarium consists of two parts which together make up more than half the radius. There is a conspicuous outer zone of lonsdaleoid dissepiments which interrupt the septa for well over one-third the radius. An inner and less conspicuous series of concentric and herring-bone dissepiments occur between the major septa, which rest irregularly at their periphery against the inner edge of the lonsdaleoid zone. There is a gradation between the outer lonsdaleoid zone, the inner zone of smaller dissepi-

ments and the incomplete and numerous small tabulae. The tabulae are inclined downward toward the axis at a moderate to steep angle and they form a concave floor in the axial region (Text-fig. 2a).

Remarks.—The nature of bunching and shortening of the septa found in the holotype is believed to be an inconstant feature. A poorly preserved specimen collected from the same area as the holotype and probably belonging to the same species (See *Occurrence* below) has five areas of bunching which are irregularly arranged.

Kakwiphyllum cf. *dux* (Pl. X, figs, 2a-c) from the Liard River Region differs from the holotype in having, in the late ephebic stage, a dilation of the septa in the tabularium, a small cardinal fossula and a different and irregular bunching of the septa. Futher collecting may show that these features indicate a new species but this form is at present compared with the type species.

Septal Structure.—The septa of the holotype are partly recrystallized but they appear to be composed of thin parallel fibre fascicles not grouped into trabeculae and arranged at right angles to the plane of the septa.

Holotype.—G.S.C. coll. no. 10569.

Occurrence.—G.S.C. loc. no. 15961. Kakwa-Jarvis Lakes area, north-east British Columbia. The holotype was collected from a talus block on the south slope of the second mountain west of Mt. Hannington, which is immediately north of the Jarvis Lakes and exposes the upper Banff and the Rundle formations. However, a poorly preserved specimen, which is probably conspecific with the holotype, was collected from the upper part of the Rundle formation at the same locality. This would suggest that the holotype may also have come from the upper Rundle.

INCERTAE SEDIS

LIARDIPHYLLUM gen. nov.

Type Species.—*Liardiphyllum hagei* sp. nov. (Pl. IX, figs, 4a-b ; Text-fig. 3a-c). Mississippian, Western Canada.

Generic Characters.—Simple, small to medium sized, trochoid to cylindrical corals in which the major septa are discontinuous and appear as vertical series of plates on the upper surfaces of the tabulae and dissepiments ; the complete and incomplete tabulae, which are gradational with a peripheral zone of lonsdaleoid dissepiments, are inclined downward axially and form a series of irregular, inverted cones with cup-shaped depressions in the axial region.

Remarks.—This genus has a superficial resemblance, in the appearance of the tabulae in transverse section, to some Silurian species of *Cystiphyllum* Lonsdale but forms included in that genus have acanthine

septa. *Liardiphyllum* is unlike any Carboniferous genus known to the author and it is thus impossible at this time to place it in a family.

Liardiphyllum hagei sp. nov.

Pl. IX, figs, 4a-b. and Text-fig. 3a-c

Description of the holotype.—The holotype is a cylindrical fragment about 25 mm. long, including the calyx but with the early stages missing, and with a diameter of 20 mm. at the base of the calyx. The specimen is almost straight, but the mouth of the calyx is tilted away from the cardinal septum which would therefore appear to be on the convex side of the corallum (Text-fig. 3a). The exterior has fine transverse rugae which are slightly irregular. Interseptal ridges are present but inconspicuous.

TEXT-FIG. 3.—*Liardiphyllum hagei* sp. nov. Holotype, G.S.C. 10571; longitudinal sections, × 2; (*a*) through calyx along cardinal-counter line, (*b*, *c*) at right-angle to cardinal-counter line, (*a*) through axis and (*b*) offset from axis, to show amplexoid nature of septa.

There are 36 to 38 major septa in the ephebic stage. They are not continuous and each is represented by a vertical series of short, slender plates occuring only on the upper surfaces of successive dissepiments and tabulae. The septa in the cardinal quadrants are more dilated than those in the counter quadrants, and all of the septa may be thickened in the axial region (Pl. IX, fig. 4b). Minor septa are present only as septal ridges on the epitheca. There are some indications of bilateral symmetry about the cardinal-counter line. The counter septum is longer and more continuous than the other septa. The cardinal septum is slightly shortened and an irregular open cardinal fossula is developed. The tabulae and dissepiments appear in transverse section as irregular circularly disposed rings.

The tabulae, which are both complete and incomplete are inclined downward axially to form a series of inverted cones with cup-shaped depressions in the axial region (Text-fig. 3b-c). There is not always a

clear separation between the tabulae and dissepiments which are large and steeply to almost vertically inclined.

Septal Structure.—The septa in the holotype are composed entirely of lamellar tissue which is continuous with the thickening of the tabular parts.

Holotype.—G.S.C. coll. no. 10571.

Occurrence.—G.S.C. loc. no. 16622, Liard Range, North-west Territories (See *Occurrence* under *Zaphriphyllum disseptum* for exact locality). Middle Mississippian.

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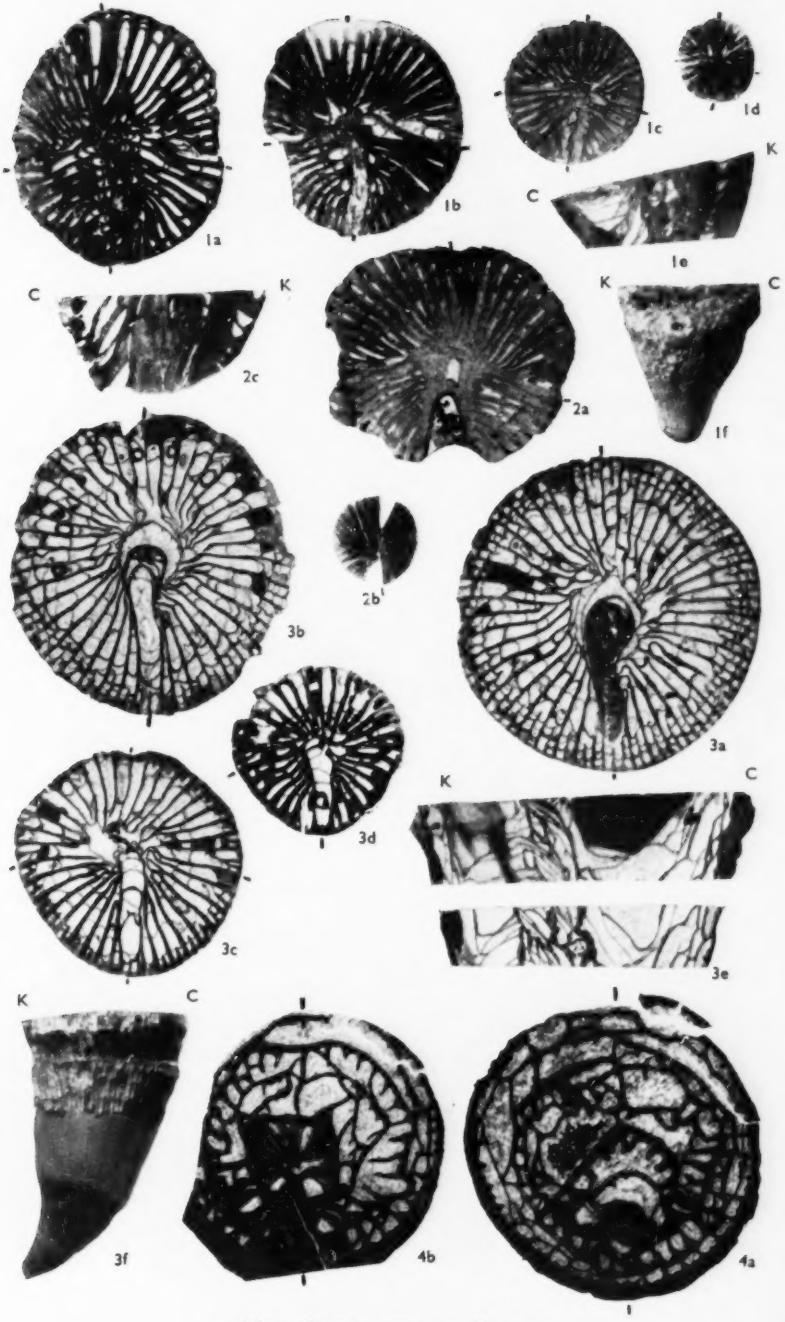
EXPLANATION OF PLATE IX

FIG. 1.—*Canadiphyllum knoxi* sp. nov. Holotype, G.S.C. 10566; (*a–d*) transverse sections, late, middle, and early ephebic and late neanic stages, × 2; (*e*) longitudinal section along cardinal-counter line, × 2; (*f*) weathered exterior, × 1.

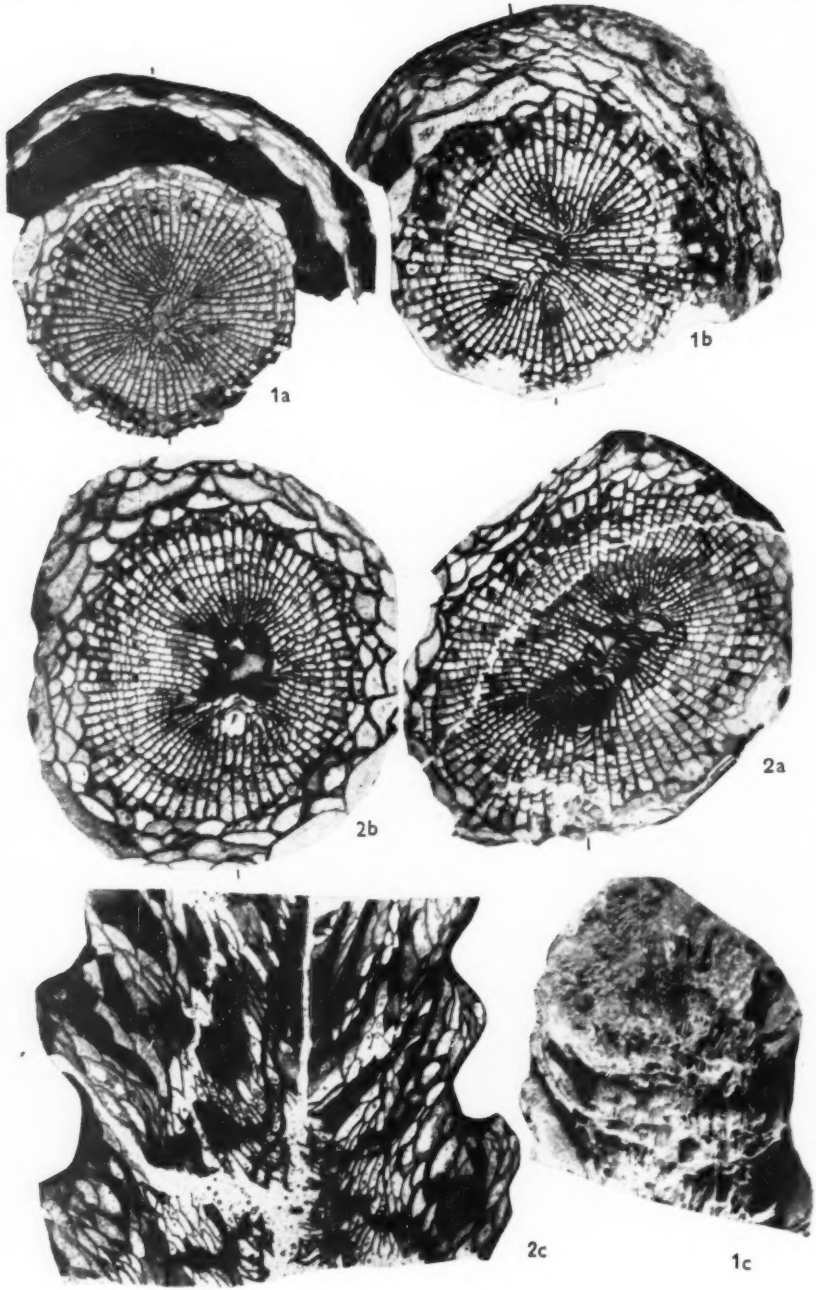
FIG. 2.—The same. Paratype, G.S.C. 10567; (*a–b*) transverse sections, late ephebic and late neanic stages, × 2; (*c*) longitudinal section along C–K line, × 2.

FIG. 3.—*Zaphriphyllum disseptum* sp. nov. Holotype, G.S.C. 10568; (*a–d*) transverse sections, late, middle, and early ephebic stages, × 2; (*e*) longitudinal section, along C–K line, × 2; (*f*) exterior, × 1.

FIG. 4.—*Liardiphyllum hagei* sp. nov. Holotype, G.S.C. 10571; (*a–b*) transverse sections, late and middle ephebic stages, × 2.



NEW CARBONIFEROUS CORALS.



NEW CARBONIFEROUS CORALS.

EXPLANATION OF PLATE X

FIG. 1.—*Kakwiphyllum dux* sp. nov. Holotype, G.S.C. 10569; (*a–b*) transverse sections, late and middle ephebic stages, × 1; (*c*) weathered external view showing nature of dissepiments, × ¾.

FIG. 2.—*Kakwiphyllum* cf. *dux*, G.S.C. 10570, from Mississippian of Liard Region, N.W.T., Canada; (*a–b*) transverse sections, late and middle ephebic stages, × 1; (*c*) longitudinal section, at right angle to cardinal-counter line, × 1.

The Distribution of Radioactivity with Depth in the Continents

By G. F. S. Hills

Abstract

The heat generated by the radioactive elements in the surface of the earth has been calculated by Evans and Goodman (1941) and by H. Jeffreys (1952). The amount of radioactivity in the depths of the continents obviously cannot be directly calculated. In the following paper two physical reasons are given for believing that the amount of radioactivity in the depths exceeds that found in the surface.

THE radioactive heat generated in each cubic centimetre of acidic igneous rocks at the surface of the continents has been measured by Evans and Goodman (1941). They found from twenty-six samples that the mean radioactive heat generated was $4 \cdot 3 \times 10^{-13}$ cal/cm.^{3} sec. The range, however, from which the mean was calculated was wide. They make the following remarks on their work: " Several hundred radioactive measurements have been made on the rocks using unusual analytic care " (p. 480). " Multiple analyses have been made on different portions of the same powdered sample of each rock. In some cases the analyses are in close agreement, indicating that the parent element and the daughter element, radium, are fairly uniformly distributed. In other cases excessive variation occurs, which is attributed to in-homogeneous distribution of radium. Such in-homogeneity appears to be usual rather than exceptional for rocks " (p. 465). " It was observed quite early (Strutt, 1905) that the concentration of radioactive elements in rocks increased with the silica content. A number of other investigators, in addition to the present work, have amply confirmed this general conclusion " (p. 477).

Jeffreys (1952, p. 280) has classified the measurements of radioactivity in a number of rocks. He gives no range but groups them by regions. He gives the mean heat of radioactivity for granite in the region of Greenland, Iceland, Scotland, Ireland, and Japan, as $5 \cdot 1 \times 10^{-13}$ cal/cm.^{3} sec., in the region of Finland as $14 \cdot 5 \times 10^{-13}$ cal/cm.^{3} sec., in the region of the Alps as $14 \cdot 9 \times 10^{-13}$ cal/cm.^{3} sec., and in the region of South Africa as $7 \cdot 3 \times 10^{-13}$ cal/cm.^{3} sec.; but marks the last named with a query. He also says (p. 277) the striking feature of the rocks is that Ra and Th are always present, though their amount, even in rocks of the same geological type, is very variable. This last remark taken together with Evans and Goodman's remark about in-homogeneity implies that radioactivity is irregularly distributed in the surface of the granite.

Whether radioactivity decreases or increases with the depth in the continents is a question to which obviously no direct answer can be

given. There are, however, two physical reasons which lead one to believe that radioactivity is greater at depth than near the surface of the continents. The first reason is connected with the total absence of water in the granite surface. Goranson's (1931) experiments show the solubility of water in fused Stone Mountain granite at 900° C. is 5·75, 8·15, 8·90, and 9·35 per cent under pressures of 1, 2, 3, and 4 kilobars respectively, where a pressure of 4 kilobars is approximately equal to 15 km. of granite. Jeffreys (1935, p. 128), commenting on this, says: "These facts suggest that much of the water in the upper and intermediate layers has been held by pressure and they have consequently failed to crystallize." This suggestion is confirmed by the velocities of the P and S waves in the continents found by seismology, for the velocities of those waves are 5·5 and 3·36 km. per sec. while those found in granite in the laboratory are 6·1 and 3·5 km. per sec. Jeffreys (1952, p. 84) concludes: "On the whole it seems to me most likely that the upper layer (the continent) is granite probably mixed with obsidian."

Near the surface the excess silica has crystallized to quartz while at greater depths it probably exists in an uncrystallized aqueous condition. As the silica near the surface, where the water could escape, crystallized to quartz, it excluded the contained water and with the water it also excluded the contained radioactivity. The cracks, veins, and pegmatites, which were formed near the early granitic surface, by the pressure of the escaping steam, were filled with quartz and other minerals which could not find a place in the silicates including the radioactive substances. These cracks, etc., have long since been denuded in the course of 2,000 million years and the radioactivity in them has been carried as sediments to the ocean.

There is a physical reason for believing that it was originally concentrated more in the lower levels of the continents than in the higher levels. This reason depends on the hypothesis that the continents were formed as the result of convection currents in the magma when the magma was in a fluid state (Hills, 1947). It is there suggested that the magma rose from the depths around the equator, at a temperature much above the melting point of olivine. Part of it travelled over the surface, cooled in contact with the atmosphere and sank at the much colder poles. The cooling of the poles would be due to the sun which produced convection currents in the atmosphere, rising from the hot equator of the magma to the cold upper layers and descending on the poles. As the magma currents in the surface approached the poles they would cool and in part crystallize. Those crystals which were denser than the magma would sink and ultimately build up the floor of the magma ocean, and those which were lighter would float. The feldspar crystals would clump together with the entangled magma and

form rafts at the two poles. After the force of convection ceased, the rafts would probably float in the magma towards the equator, where gravity is least, thus later, when they came above the ocean, forming the continents of Laurasia and Gondwanaland with the Tethys in between them.

The magma, which was entangled with the feldspars, would be more radioactive than the deep underlying magma ocean, because it would have been reduced in volume by the sinking and floating crystals which formed out of it. Further, as the deep magma ocean became shallower by crystallization it would become more radioactive. Goldschmidt (1954) says: "The large radius of thorium makes it unfit to enter many of the important early silicates, such as the simpler orthosilicates or metasilicates of magnesium and divalent iron . . ." (p. 427); a similar remark is made as regards uranium (p. 562). The rafts (which became the continents) floated in the magma and the additions, which were made to them from the magma, must have been made from below. The entangled magma which entered them would have become more radioactive as time went on. For this and the previous reason, radioactivity would be expected to increase with depth in the continents. How much it would increase is difficult to calculate, but if the observations on the Alps and Finland, given by Jeffreys, in which some of the lower levels have been brought to the surface, can be relied on, it would be nearly three times that at the surface.

When ultimately the residual magma had become too viscous to permit the separation by gravity of the floating and sinking crystals, it would cool into the intermediate layer. There would then have been three layers, (i) the floating crystals together with the entangled magma, (ii) the residual magma, and (iii) the deep layer formed by the sinking crystals. It will be noted that three layers of these compositions have been distinguished by seismology. The residual magma would for some time be in a convective state and the radioactivity in it would be expected to be more or less uniformly distributed. Jeffreys (1941, p. 834) remarks that "The chief recent result is the remarkable resemblance both in mean radioactivity and in scatter between the oceanic and the plateau basalts". It is surprising that on the basis of Evans and Goodman's (1941) experiments, Slichter (1941, p. 568) calculates the heat-generating power of the plateau basalts to be $1 \cdot 0 \times 10^{-13}$ cal/cm.^{3} sec., while Jeffreys (1952, p. 280) finds for plateau basalts $2 \cdot 6 \times 10^{-13}$ cal/cm.^{3} sec. and for oceanic island basalts $2 \cdot 9 \times 10^{-13}$ cal/cm.^{3} sec. The extensive plateau basalts, such as those of the Deccan, are regarded as representative of the basaltic substratum, though they have lost their water since they were erupted.

The sinking crystals of the lower layer, nearly 3,000 km. deep, by

packing together under pressure would exclude most if not all of the liquid magma and therefore the radioactivity of the lower layer would be expected to be negligible, though perhaps the magma near the top of that layer would have become so viscous that some of it could not escape from the interstices of the crystals.

The remark made by Evans and Goodman (1941, p. 477) that the concentration of radioactivity in the specimens examined increases with their silica content receives an explanation from the convection theory. The excess silica, over that required to form the silicate crystals, would be in an aqueous state when in the magma and would enter into the magma entangled with the feldspar crystals. The latter crystals would be without water and the main and probably the only source of water in the continents would be that which was held in an uncombined state with the aqueous silica.

Shand (1943, p. 228) has defined granite as containing 25 per cent to 40 per cent of quartz and he says (p. 305) that the plateau basalts of the Deccan contain 2·4 per cent to 5 per cent of quartz. It follows that the quartz at the surface is eight or ten times that in the plateau basalts. The quantity of aqueous silica originally in the surface of the continents and therefore the original quantity of radioactivity would be expected to be eight to ten times as great as that in the plateau basalts. Accepting Evans and Goodman's finding of $1 \cdot 0 \times 10^{-13}$ cal/cm.^{3} sec. as the heat generated by radioactivity in the plateau basalts it seems to follow that the heat generated in continents on the average would be at least eight to ten times as great as that in the plateau basalts. This would be in accord with the reasons given for believing that the lower levels of the continents are richer in radioactivity than the surface levels.

It is of interest to compare the heat generated in the continents and in the basaltic substratum with the heat output from the surface of the continents. The latter according to Slichter (1941, p. 574) is little explored and regional values, within the range $0 \cdot 6 \times 10^{-6}$ and $2 \cdot 5 \times 10^{-6}$ cal/cm.^{2} sec., are entirely possible though the results tend to support the view that the mean is not far from $1 \cdot 2 \times 10^{-6}$ cal/cm.^{2} sec. Jeffreys (1952, p. 282) gives a range from $1 \cdot 0 \times 10^{-6}$ to $2 \cdot 07 \times 10^{-6}$ cal/cm.^{2} sec. for a number of boreholes and a mean can be calculated for forty boreholes of $1 \cdot 24 \times 10^{-6}$ cal/cm^2 sec. Following Jeffreys, the continents are taken as 12 km. thick and the basaltic substratum as 24 km. thick (1952, p. 172), and taking the average heat generated in the continents at the figure of 8×10^{-13} cal/cm.^{3} sec. and in the basaltic substratum as 1×10^{-13} cal/cm^3 sec., it will be seen that the heat escaping from the surface would be $(12 \times 8 + 24 \times 1)\ 10^{-8} = 1 \cdot 2 \times 10^{-6}$ cal/cm.^{2} sec. which as Slichter (1941) suggests is not far from the heat output of the continents.

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63 WEST END AVENUE,
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Interpretation of the Gravity Field of the Eastern Alps

By M. H. P. Bott

Abstract

It is demonstrated that a deficient mass reaching within 10 km. of the surface is responsible for the central belt of negative gravity anomalies in the Eastern Alps. Hypotheses for explanation of the deficient mass are discussed and it is concluded that the presence of unexposed granite in addition to crustal downwarp is the most satisfactory of these. The position of part of the mass deficiency is irreconcilable with existing isostatic hypotheses and an alternative hypothesis is proposed. The development of the granite mass deficiency is briefly discussed.

I. Introduction

IT has been known for a long time from pendulum observations that there is a large negative gravity anomaly over the Alps. The mass deficiency responsible is usually thought to exist as a crustal thickening and downwarp whereby the lighter upper layer or layers are thickened and depressed into regions normally occupied by denser material. The correlation in position between the negative anomaly and the present mountain chain, and the approximate equivalence of the mass of the mountains with the mass deficiency beneath, support isostasy in a general way. A crustal downwarp is consistent geometrically with the Airy-Heiskanen type hypotheses of isostatic compensation.

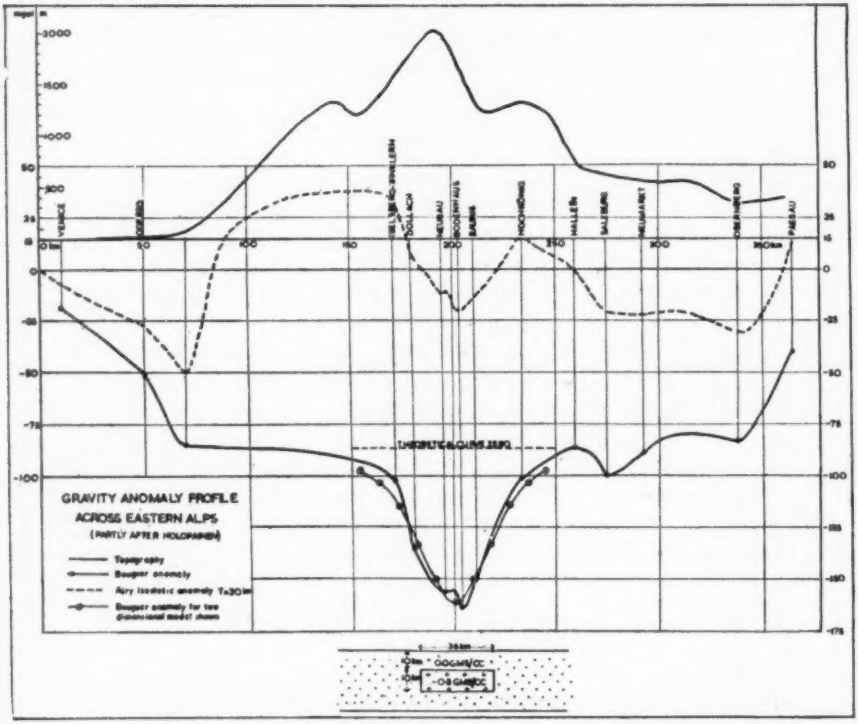
Perhaps the greatest outstanding problem in interpreting the gravity field of the Alps is that the Bouguer gradients are often greater than would be expected from a simple crustal downwarp, for which the top of the mass deficiency must be at a considerable depth. There have been some attempts to account for these gradients but as will be seen later all of these seem unsatisfactory.

The object of this paper is to investigate the nature of the mass deficiency. For convenience the actual interpretation is restricted to the Eastern Alps as Bouguer profiles are available for this region at the end of the paper on the isostatic structure by Holopainen (1947).

II. Physical Interpretation of a Profile from Venice to Passau

Holopainen's Profile II, which crosses the Alps from Venice to Passau, is reproduced in a modified form as Text-fig. 1. The Bouguer anomaly and the most satisfactory Airy isostatic anomaly are shown. A broad negative Bouguer anomaly with steep marginal gradients covers the whole of this route. A large central negative anomaly of about − 70 mgals is superimposed, and coincides with the region of greatest elevation and the axial structural belt. This central negative anomaly is now studied as a two-dimensional feature to determine

the depth of the mass deficiency causing it. The pendulum measurements at Iselsberg, Winklern and Dollach, which are used for the estimate of maximum Bouguer gradient are apparently reliable and are not prejudiced by assumptions in reduction (such as density). The maximum gradient is then 3·3 mgals/km. for over 8 km. The minimum anomaly is taken as 75 mgals below the background value.

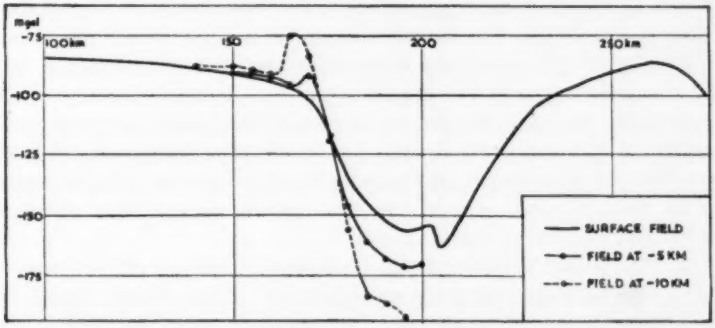


TEXT-FIG. 1.—A gravity profile across the East Alps. For comparison the gravity field for a two-dimensional model is included.

Bullard and Cooper (1948) describe an absolute method for estimating the maximum depth of the masses causing a given anomaly. In the first stage a numerical integration from the surface field provides an estimate of the field at a chosen depth below the surface. It is then possible to calculate the field at greater depths by relaxation. When the calculated field oscillates violently in the opposite sense to the surface field the greatest depth at which the masses could be concentrated has been passed. Using this procedure it is deduced that the top surface of the mass deficiency responsible for the central

negative anomaly lies less than 10 km. below the surface. The surface field and calculated fields at depths of 5 and 10 km. are shown in Text-fig. 2.

This result can be verified by an alternative method of depth estimation. If the mass deficiency were concentrated at a single point, or uniformly throughout a sphere, the ratio of maximum anomaly to maximum gradient would indicate a depth of 19·4 km. for the point or centre of the sphere. Alternatively if the mass deficiency were concentrated uniformly along an infinite horizontal line source its depth would be 14·6 km. However, for each of these trials the predicted distance between the points of inflexion is considerably shorter than the actual distance, by 20 + km. for the line source. Hence, assuming



TEXT-FIG. 2.—An illustration of the application of Bullard's and Cooper's method for the estimation of the depth to the masses producing the central negative anomaly.

a two-dimensional structure, the first conclusion is that the top surface is less than 15 km. deep, and that its width, for infinite density contrast, is at least 20 km. For the next stage it is assumed that the anomaly is caused by a two-dimensional horizontal strip of constant width 20 km., infinitesimal thickness, and uniform mass deficiency per unit area. A graphical calculation shows that the depth of the plate is 12 km. and that it is still too narrow by 10 km. A recalculation for a width of 30 km. establishes a maximum depth of 10 km.

Calculations for two-dimensional rectangular models with an assumed density contrast of − 0·2 gm./c.c. confirm that the mass deficiency for this contrast reaches within 7 km. of the surface whatever the width. The top surfaces for intermediate density contrasts would be expected to lie in intermediate positions.

If the deficient mass possessed radial symmetry its depth might be a little greater than these estimates. However, Holopainen's

Bouguer map indicates plunging linear rather than radial form for the anomaly. Nor is there any reason to suppose that marginal mass surplus is responsible for the steep gradients as there are no obvious marginal positive anomalies with steep outward gradients.

The unavoidable conclusion is that the *top* surface of the mass deficiency must be within 10 km. of the surface and is probably considerably closer. This deduction is independent of density assumptions.

III. Geological Interpretation

Various geological hypotheses are now discussed in relation to the physical conclusions reached above.

(1) Schwinner (1929) explains steep gravity gradients in the Alps by postulating in addition to a downwarp of SIAL, marginal dykes of denser SIMA extending upwards towards the surface. The downwarp is responsible for the main negative anomaly while the dense SIMA dykes give marginal positive anomalies which increase the gravity gradients into the negative region. There is, however, no systematic support from the gravity field for the expected marginal positive ridges, especially for the profile illustrated where the central negative is superimposed on the main broader negative. There seems to be no geological support for this hypothesis and it is rejected as an explanation of the gradients.

(2) Holopainen (1947) analyses the isostatic structure of the Eastern Alps, and he finds that the Airy hypothesis with a 20 km. depth of compensation is most satisfactory. Remanent isostatic anomalies are found for regions of steep Bouguer gradients and particularly for the central anomaly discussed here (see Text-fig. 1). Holopainen attributes the central isostatic anomaly to an uncompensated additional root, still at the base of the crust. This hypothesis is clearly inconsistent with the physical interpretation above as it places the top of the mass deficiency at a depth of 20 km. (see Holopainen's Profile II*a*).

(3) Umbgrove (1948) reinterprets Holopainen's Profile II and suggests the existence of three separate roots. The lower two of these are placed conventionally at the bases of the " granitic " and intermediate layers. The uppermost root which lies directly below the main mountain belt is responsible for the central negative anomaly with steep gradients. It is in the form of a thickening and downwarp of the crystalline cores of the nappes at the expense of the " granitic " layer. This explanation is not satisfactory as metamorphic rocks in bulk have a density of about 2·8 gm./c.c. which is greater than the density of granite.

(4) It might be suggested that the central anomaly is caused by less dense sediments below. This is highly unlikely as metamorphic rocks outcrop in this belt. Holopainen and Umbgrove have already

pointed out that the steep gradients bordering the *overall* negative anomaly are due to the Molasse and Lombardic troughs of light sediments.

(5) The most satisfactory hypothesis seems to be that this belt is underlain by a large mass or masses of granite. It is now well known that large negative Bouguer anomalies are associated with post-tectonic granites and that the anomaly is caused by direct density contrast between metasedimentary and metavolcanic rocks and the granite itself which is 0·05–0·20 gm./c.c. less dense. Furthermore, post-tectonic granites are characteristic of orogenic folded belts and would be expected under the Alps despite the scarcity of surface exposure. This postulated granite mass under the Eastern Alps is not yet uncovered by erosion.

It is noted that Murphy (1952) suggested this hypothesis in concluding a paper describing gravity survey in Ireland. He states: "... it seems to be a universal property of granite to be less dense than the consolidated sediments excepting sandstones. It is a large step from local to regional gravity anomalies but it does seem possible that granites, with densities similar to those mentioned, could make a major contribution to the low Bouguer anomalies encountered over mountain ranges."

IV. Isostatic Considerations

It has been shown that a considerable portion of the East Alpine sub-surface mass deficiency lies at a depth shallower than predicted by Airy's hypothesis of isostasy. If a rigid application of Airy's hypothesis be accepted, this shallow mass deficiency must be uncompensated by mountains. However, the correlation between the highest mountains and the central negative anomaly demonstrates that this is not so. Hence Airy's hypothesis and its variations are inadequate representations of compensation for the Eastern Alps.

It is proposed that the isostatic compensation of this region is present in the following two forms at least:—

(1) Concentrated as downwarps at the bases of the crustal layers, and mainly at the Mohorovičić discontinuity (compensation of Airy–Heiskanen type).

(2) As less dense intrusive masses normally within the top 10 or 20 km. of the crust.

It is thought that the doming and uplift of granites elsewhere and of mantled gneiss domes are also isostatic phenomena of type (2).

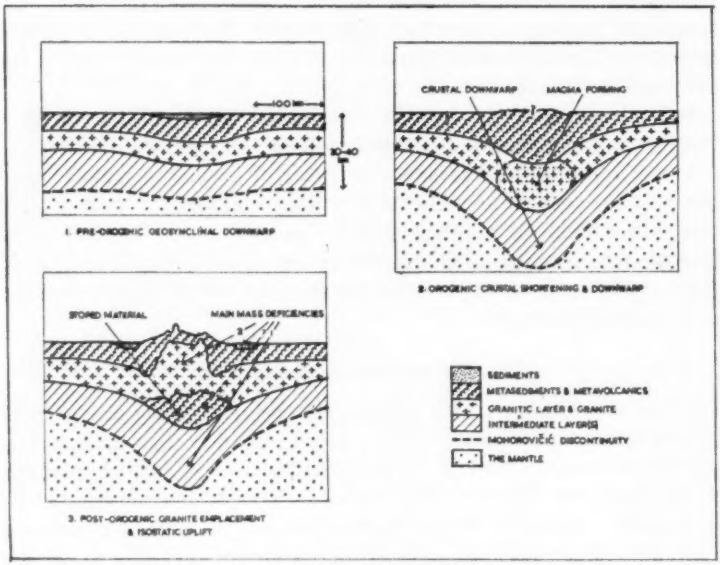
Holopainen's estimate of 20 km. for the crustal thickness in the neighbourhood of the Alps is not in agreement with the larger estimates of about 40 km. from seismology (Gutenberg, 1943). The discrepancy

is due to the assumption that all the mass deficiency is at the base of a one layered crust.

V. The Development of the Mass Deficiencies

It is thought that the mass deficiencies developed as follows:—

(1) Crustal thickening accompanying the Alpine orogeny thickened and depressed the lighter crustal layers. At this stage the mass deficiency is entirely at the base of the crust or of crustal layers.



Text-fig. 3.—Sections illustrating the hypothesis proposed for the development of the mass deficiency.

(2) Part of the mass deficiency is later transferred to a higher crustal layer by virtue of the formation of granite and now resides as a granite mass which has not yet been exposed by erosion.

The process is most easily understood if the crust consists of dense metasedimentary and metavolcanic rocks (density about 2·8 gm./c.c.) overlying a granitic layer (2·6–2·7 gm./c.c.), an intermediate layer and finally the mantle (Bott, 1953). During and shortly after the main movements increased radioactive concentration and other sources of heat combine to melt the granitic layer which as magma invades the overlying metasediments by the stoping mechanism, with secondary

forcible intrusion and metasomatism, and consolidates as a batholith. Stoped metasedimentary material accumulates on the floor of the original magma chamber so reducing the original mass deficiency at the base of the granitic layer. The downwarp at the base of the crust will remain but will decrease in size with each subsequent period of uplift of the mountain range. This hypothesis is illustrated in purely diagrammatic form in Text-fig. 3.

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Hantkenina alabamensis Cushman and Some Related Forms

By Tom Barnard

Abstract.

Some variations in the apertures of *Cribrohantkenina* are arranged in morphological series. The development of the "cribrate" aperture and its relation to other biocharacters, such as the shape of the chambers, development of spines, and globosity of the chambers, is discussed, as also the status of the subgenera of the genus *Hantkenina*.

I. Introduction

SINCE 1925, when Cushman selected *Hantkenina alabamensis* as the genotype for his genus *Hantkenina*, various authors, notably Thalmann, Howe, Cushman, Bronnimann, and Shokhina, have described new species and sub-genera. Thalmann (1942) introduced the sub-genera *Hantkenina* ss. *Aragonella*, *Applinella*, and *Cribrohantkenina*, stating that "the morphologic features of the tests of the different species of the genus *Hantkenina* Cushman, 1924, and their stratigraphic ranges justify a subdivision of the genus into several sub-genera . . ." Through some oversight the sub-genus *Hantkeninella* was not described although mentioned in the range chart, and it was left to Bronnimann (1950) to designate a type-species. Five sub-genera have now been proposed.

As with other foraminifera a large amount of variation occurs in some of the species, intergradation is common, and it appears undesirable to erect sub-genera, adding to an already overwhelming nomenclature. As the number of species assigned to each sub-genus appears to be small and as a serious student of "planktonic" foraminifera must know the majority of these, it seems illogical to erect sub-genera. For the stratigraphical palaeontologist a knowledge of the general trends of evolution is important.

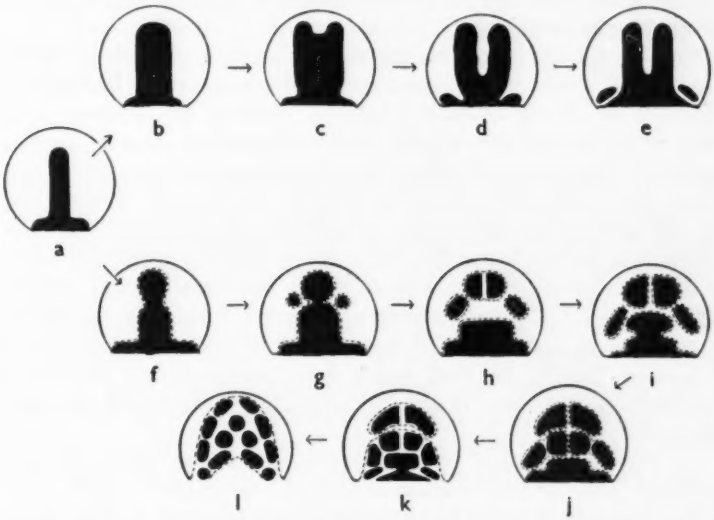
Bronnimann (1950) described what is termed a bioseries of *Hantkenina*; this appears to be a plexus of descent, a cluster of bioseries showing the general evolution of the genus. Whilst studying the variation in the apertures of a number of foraminiferal genera the present author was impressed by the numerous variants which occur in different individuals of the species of *Hantkenina sensu lato*, particularly in those belonging to the sub-genus *Cribrohantkenina* Thalmann.

The following paper largely consists of a study of topotype material of *Hantkenina alabamensis* Cushman from the Upper Eocene, Zeuglodon Bed, Cocoa Post Office, Alabama, kindly supplied by the National Museum, Washington.

2. The Apertures of Cribohantkenina Thalmann

The sub-genus *Cribrohantkenina* was established by Thalmann on account of the tendency of some forms to develop a multiple aperture. The present study shows that these apertures are extremely variable, and that there is a passage from the simple arch-shaped aperture of *Hantkenina sensu stricto* to the complicated multiple aperture.

The shapes of the apertures appear to follow two main morphological series (both taken from the simple to the more advanced or complicated).



Text-fig. 1.—A diagram to show the variation in the apertures in *Hantkenina*.
1 *a–e*. A morphological series showing the downward growth of a " tooth ".
1 *a–l*. A morphological series from the simple slit-like to the multiple cribrate aperture.

Care was taken to ensure that the specimens were adult, the shape of the apertures during ontogeny is dealt with later in the paper. The apertures in the following morphological series are all found on forms with inflated or globose chambers, this latter feature appearing for the most part in the ultimate and penultimate chambers.

The first and simpler of the series is represented in Text-fig. 1 *a–e*. The typical elongate slit-like aperture of *H. alabamensis* Cushman, with two basal lateral extensions, tending to extend downwards and backwards into the umbilicus, is shown in Text-fig. 1*a*. A general tendency for the aperture to broaden is illustrated in Text-fig. 1*b*, but the same general shape and smooth outline of *H. alabamensis* Cushman are

maintained. The tendency for the aperture to broaden reaches its maximum in Text-fig. 1*c*, but a new trend of development now begins ; the top of the almost quadrate aperture becomes indented, a thick prolongation (a " tooth ") grows downwards into the aperture (Text-fig. 2C), and at the same time the two basal lateral portions of the aperture become constricted.

The " tooth " grows until it protrudes about two-thirds of the distance across the aperture, the basal constriction continues (Text-fig. 1*d*, *e*) until the small subsidiary lateral apertures are produced (Text-fig. 1*e*), which marks the culmination of specialization in the first morphological series.

Text-fig. 1*a*, *f–l*, represents the second morphological trend, where the general tendency is to produce a multiple aperture. The typical aperture of *H. alabamensis* Cushman (Text-fig. 1*a*) becomes constricted about half-way down, forming one large central, circular aperture. Two small subsidiary lateral apertures are separated at this stage, as shown in Text-figs. 1 *f–g* and 2B. In Text-fig. 1*h* the larger circular central aperture becomes constricted and splits into two equal portions, at the same time the remainder of the basal aperture is broad and almost quadrate. Text-fig. 1*i* shows this basal part to enlarge upwards and to become constricted in the same way as before, culminating in Text-fig. 1*j*. The constriction and splitting is carried still further in Text-fig. 1*k*, until finally a complex sieve-like aperture is developed in Text-figs. 1*l* and 2F. Still more complicated apertures are sometimes attained.

At this point it must be emphasized that all the specimens were obtained from one small sample of rock, so that an evolutionary series is not implied. A study of successive populations will perhaps show that a passage from the simple to the complex apertures does take place in time, but this must be left to a worker more conveniently situated, who is able to systematically collect the material horizon by horizon. The progression from the simple to the complex aperture within the genus as a whole, or perhaps within an abortive off-shoot from the main evolutionary trend of the genus, reminds the author of similar apertural complications which occur in the cribrimorph polyzoa. Bronnimann (1950, Fig. 2) shows *H. bermudezi* Thalmann, *Cribrohantkenina*, to be an end form of development, reaching the climax of specialization within the group.

Bermudez (1937 *b*) and Bandy (1949) discuss the development of the apertures during ontogeny, and have shown a progression from a simple aperture in the early chambers to an advanced cribrate aperture in adult chambers. The present author has not been able to find any gentle passage from the simple arched aperture to the complicated multiple aperture as these authors suggest. There appears to be in all the

specimens examined a rapid jump from the normal aperture of the adult *H. alabamensis* Cushman, which usually occurs until the penultimate whorl, to a more advanced aperture in the adult chambers. A study of more material may prove a gentle passage in the shape of the aperture, to be the case in most forms. The rate of appearance of this bio-character will be discussed later. The series of changes in the apertures both in ontogeny and possibly in phylogeny appears to support recapitulation in this biocharacter. The appearance of the advanced aperture late in the range of the genus appears to be phylogerontic, and from the evidence obtained from the ontogeny the appearance late in life of the complicated aperture may be a gerontic character. In view of the large number of individuals possessing no other abnormalities this apertural change is not due to senility.

3. The Shape of the Chambers

As can be seen from Bronnimann (1950, Fig. 2) the shape of the chambers appears to vary with time. In early species the chambers are often irregular, drawn out in spinose projections giving an extremely lobulate periphery. This lobulation is increased along the line of certain abortive off-shoots.

Anagenesis takes place from the irregular chambers of *H. mexicana* Cushman and *H. dumblei* Weinzierli and Applin to *H. alabamensis* Cushman, with an almost smooth periphery. Catagenesis then seems to take place from *H. alabamensis* Cushman to forms with globose chambers *H.* (*Cribrohantkenina*) *bermudezi* Thalmann. In some forms of the latter this lobation of the chambers takes place early in ontogeny.

4. Development of Spines

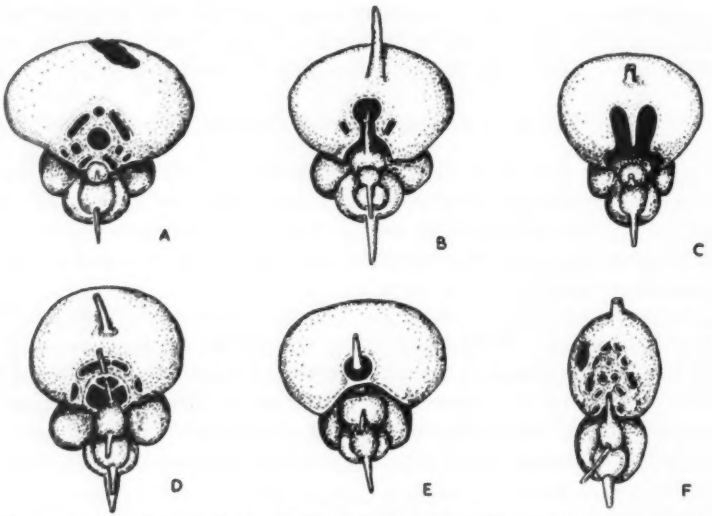
Bronnimann (1950, Fig. 1) shows the morphology of the test of *Hantkenina*. Slight confusion arises from the terminology of the spines. In nearly every case the spine occurring on each chamber is in a position anterior to the posterior suture of the chamber, and in the opinion of the author should be called an anterior spine; otherwise it gives the impression that the end chamber has two spines.

The spines in early forms are blunt and central, being on the prolongations of the chambers of *H.* aff. *mexicana* Cushman and *H. dumblei* Weinzierli and Applin. There is a general tendency, with time, for the spine to become narrow and elongate, and to move anteriorly so that finally they occur almost at the suture (i.e. at the junction between the apertural face and the periphery). In several off-shoots *H. australis* Finlay and *H. thalmanni* Bronnimann, there is a tendency for the spines to shorten and become obsolete. In *H. bermudezi* Thalmann, on the end chamber only, the spine sometimes occurs on the apertural face.

5. A Discussion of the Series of Biocharacters

As is to be expected when dealing with a plexus of evolving forms, the rates of evolution in one character varies from that of another, so that the appearance of changes in one feature need not be, and very seldom is, in step with that of another.

Not only does this appear to be the case in time, but individual variation retards or accelerates the appearance of a feature in ontogeny, and in foraminifera this is often the cause of much of the variation within the group.



Text-fig. 2.—Camera lucida drawings of six specimens to show variation in aperture, position of spine in relation to the aperture, and the degree of globosity of the final chamber. All drawings on the same scale. × 110.

As has already been stated the modified apertures usually occur on swollen chambers. The degree of globosity, however, seems to bear no relationship to the degree of complication of the aperture. Although Text-fig. 2F shows an intermediate stage of globosity between the compressed whorl of *H. alabamensis* Cushman and the globose stage of some specimens of *H.* (*Cribrohantkenina*) *bermudezi* Thalmann, the aperture has reached an advanced stage of development.

The highly globose forms shown in Text-fig. 2B and 2E show simple but constricted apertures. In *H. alabamensis* Cushman and *H.* (*Cribrohantkenina*) *bermudezi* Thalmann the number of chambers to the whorl varies slightly between four or five; this, together with variation in the position and length of spines, gives a wide variety of forms.

The position and length of the spines, together with the variation in the number of chambers in the whorl, often effect the aperture in the ultimate chamber and add further complications. A few modifications in the aperture are shown in Text-figs. 2 B, D, and E. Text-fig. 2B shows the spine of a chamber of the preceding whorl protruding into and restricting the aperture of the end chamber. Text-fig. 2E represents a form in which the spine is placed nearer to the anterior margin of its chamber and slopes forward at a smaller angle than in Text-fig. 2B. This spine protrudes into the aperture, but goes through, the aperture appearing constricted round it.

A number of forms with more complicated apertures is represented by Text-fig. 2D. In this specimen the spine protrudes through the aperture, part of it being firmly cemented to the constricting walls and forming a dividing line down the centre of the aperture. The latter is yet another variation in the modification of the aperture, and is not on the two morphological series mentioned above but cuts across them, modifying both.

In Text-fig. 2D " threads " of calcite constrict the main aperture and are fixed to the spine, being about the same thickness as the spine.

6. Conclusions

Although the emphasis has been placed on the variations in the aperture in the end forms, variations in other biocharacters are present but less spectacular. As can be seen from Bronnimann (1950) the genus *Hantkenina* is an evolving plexus of forms with intergradations not only between the species but also between the sub-genera. The species are represented by a number of forms " clustered " around the holotype, the sub-genera are arbitrary divisions and in the opinion of the author the use of them should be discouraged, for they not only draw attention away from the main issue, the evolving plexus, but appear to serve no useful purpose.

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Ice-Borne Boulders in the Macduff Group of the Dalradian of Banffshire

By John Sutton and Janet Watson

Abstract

The paper describes a horizon of greywackes outcropping on the coast near Macduff, Banffshire, and containing large boulders of igneous and metamorphic rocks. This horizon belongs to the Macduff Group of the Upper or Banff Division of the Dalradian. It is suggested that the boulders may have been dropped into the greywackes from floating ice.

Introduction

In the course of a general study of the Dalradian rocks of the Banffshire coast, we encountered in the Macduff Group, the youngest of the four groups into which Read (1923) divided the Banff Division, a boulder-bearing deposit. The appearance of this rock suggests that the boulders might have dropped from floating ice while the bulk of the rock was accumulating on the sea-floor.

The Banff Division contains grits, greywackes, slates, and impure calcareous rocks, which extend over much of Banffshire and Aberdeenshire, in north-east Scotland. These rocks are probably the stratigraphical equivalents of the upper part of the Dalradian succession in the central and south-west Highlands. The well-known Schichallion boulder bed, which has been accepted by some authorities as of glacial origin, forms a part of the Blair Atholl Group and lies near the bottom of the Dalradian succession of Perthshire. If the Banffshire boulder-bearing bed is a glacial deposit, as we believe it to be, we have the possibility that the Scottish Dalradian contains two quite distinct ice-borne deposits; the Schichallion boulder bed low in the lower Dalradian and the Banffshire bed in the upper part of the Dalradian succession.

General Characters

The chief exposure of boulder-bearing rocks occurs half a mile east of Macduff Harbour, on a low promontory immediately behind the slaughter-house, which is the most easterly building on the road to Tarlair swimming pool. The National Grid reference of this exposure is 714648. A second outcrop, near high-tide mark in the bay east of Head of Garness, lies 2 miles to the east of Macduff (grid reference 747647). The rocks between the two localities are both folded and faulted, and it is therefore not possible to ascertain whether the exposures lie on exactly the same horizon, but they are not separated by any great thickness of sediments.

At Macduff the boulder-bearing rocks lie in the centre of a small syncline whose axis trends N. 15° E. and plunges northward at 10° into

the sea. The rocks consist of graded greywackes which are practically uncleaved and show a low degree of metamorphism for Dalradian metasediments, small biotite flakes being present in the matrix.

The boulder-bearing horizon, about 15 feet in thickness, contains occasional fragments of igneous and metamorphic rocks ranging from a few centimetres to a metre in diameter (see Text-fig. 1). The boulders form only a very small proportion of the deposit, but nevertheless, one or two can be found in most surfaces of a few square metres. Erosion has laid bare the curved bedding planes of the folded rocks and these, combined with the sections on vertical cross-joints, provide three-dimensional views of the deposit. The almost complete lack of inland exposures makes it impossible to follow the horizon along the strike.

The Graded Greywackes of the Matrix

The graded greywackes which form the matrix of the boulder-bearing bed are dark compact-looking rocks occurring in beds which are, in this locality, seldom less than 15 cm. or more than 70 cm. in thickness. Each bed shows a marked grading, the maximum size of the particles diminishing upwards, but the sediment is badly sorted and mixtures of coarser and finer particles can be seen at every level. The clastic grains reach a maximum size of about 2 mm.; they are composed of subangular grains of quartz and feldspar with occasional rock fragments.

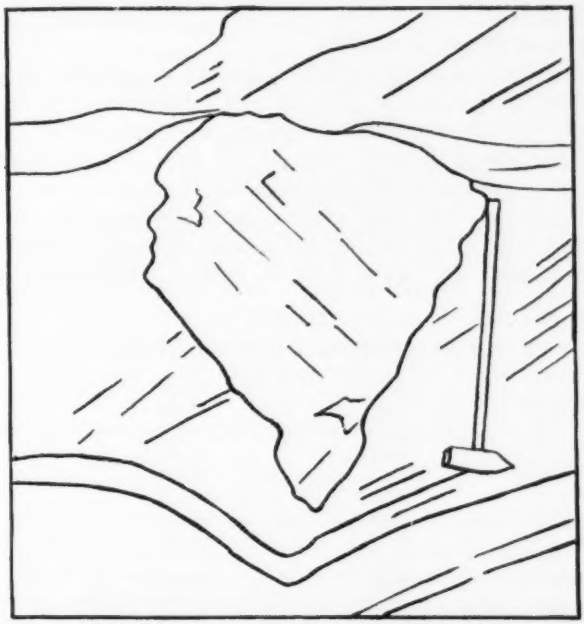
The finer and originally more muddy parts of the deposit have recrystallized to a fine-grained mosaic of quartz, feldspar, and biotite. At the base of a graded bed a pale-coloured sandy layer is sometimes distinguishable, and traces of small-scale current bedding may be seen in it.

The Boulders

The boulders are in every way distinct from the matrix in which they lie. With the possible exception of some small limestone pebbles, the boulders and pebbles, whether igneous or metamorphic, are much more coarsely crystalline than the matrix and must have existed as crystalline rocks at the time of their incorporation in the Macduff Group.

Even the smallest of the pebbles (about 5 cm. across) is many times larger than the biggest of the clastic grains found at the base of one of the graded beds of the matrix. Most range from 10 to 25 cm. in diameter; the largest are about a metre across. In general the larger boulders are the most angular, their edges being indented in an irregular fashion. A few of the smaller pebbles have flat faces meeting at acute angles, though none could confidently be claimed as facetted. Most of the small pebbles are reasonably well rounded (0·6 to 0·8 as judged visually and expressed on Krumbein's scale).

It must be emphasized that the boulders and pebbles make up a very small part of the deposit and are arranged without any strict regard to the bedding. It appears to be probable that most of the smaller fragments lie near the upper surfaces of beds, for the pebbles and boulders are more common on the bedding planes exposed over the outcrop than they are in the joint surfaces at right-angles to the bedding planes. It is quite clear that the bedded deposit had formed before the boulders were added, for the bedding is markedly depressed below the fragments,



TEXT-FIG. 1.—Boulder in greywacke, Macduff. The oblique lines indicate joints. The hammer handle is 75 cm. long.

while the larger fragments cut across the bedding and may lie in more than one graded deposit. The disturbance below fragments is more marked than that above, showing that this feature is not the result of compaction alone.

The attitude of some of the larger boulders, such as that illustrated in Text-fig. 1, supports the idea that the fragments fell into the deposit. The boulder in the text-figure, a light grey feldspathic type with a conspicuous orange-weathering crust, can be seen on a joint plane facing south at the seaward end of the promontory below the slaughter-house at Macduff. It is about a metre across and appears to be roughly conical, with the apex pointing downwards. Its weight must be of the

order of half a ton. The flattish top bulges upward from the top surface of a graded bed, and the apex projects downwards to the bottom of the same graded bed. It seems most unlikely that the boulder could have remained in this position while the graded bed accumulated around it. If the boulder had fallen into the deposit from above, however, it might have sunk until its top was roughly level with the sea-floor, and been supported by the mud around it. There is no evidence that boulders sank far into the bedded deposits, for the bedding planes above many fragments can be seen to be undisturbed, and such penetration is not to be expected, since boulders dropped into contemporary deposits are known to lie near the surface.

The boulders and pebbles consist of igneous and metamorphic rocks, the former predominating. All the larger boulders (over 60 cm. in diameter) that we have found are of igneous types, grey or pale pink syenitic rocks being the most common; all those that have been sliced are coarse-grained feldspathic varieties rich in plagioclase and poor in potash feldspar. The grey syenitic rocks are made up of altered plagioclase with a little calcite and a small amount of chlorite. An analysis of one such rock is given in Table I, which shows it to be

TABLE I

Analysis of boulder in greywackes, Macduff

SiO_2	59·00
Al_2O_3	22·60
TiO_2	0·13
Fe_2O_3	0·42
FeO	0·70
MgO	0·31
CaO	3·92
Na_2O	7·00
K_2O	2·70
P_2O_5	0·05
MnO	0·02
CO_2	1·30
H_2O+	n.d.
	98·15

Analyst: R. C. Sinha

a sodic syenite. Another and less abundant variety of syenite consists of an involved intergrowth of albite-oligoclase with some potash feldspar and chlorite.

The next most abundant group after the syenites consists of trondhjemitic and granodioritic rocks, while rarer pebbles of pegmatite and vein quartz have been found. The granodioritic and trondhjemitic types often show a slight streakiness, and many are probably best classed as gneisses. In their variable grain size, the irregular outline of

their feldspars and the frequent signs of porphyroblastic growth, these rocks resemble the coarse plagioclase-rich gneisses that can be found in the Moine or Pre-Cambrian injection-complexes of the Highlands.

The metamorphic rocks include siliceous varieties which are coarsely crystalline and which were metamorphosed before incorporation in the bed. These are dark grey siliceous granulites, formed of a mosaic of quartz, altered plagioclase, rare potash feldspar, and muscovite, and purer quartzites composed of a slightly drawn-out mosaic of quartz with small patches of altered feldspar. They are comparable in type to some members of the Moine Series.

The other type of rock we have observed in the boulder-bearing bed occurs as small and usually angular fragments of fine-grained porcellanous limestone. It appears to have undergone only the low-grade metamorphism to which this part of the Macduff Group has been subjected, and in our opinion was probably incorporated in the bed as an unmetamorphosed rock. The limestones are pure carbonate rocks composed almost entirely of carbonate grains with only an occasional quartz or iron oxide particle. One specimen consists of small spheres of fine-grained calcite, each ringed by slightly larger crystals. It might be tentatively interpreted as an altered oolitic limestone. The source of these fragments is a question of great interest. We have not seen limestones as pure as this in the Macduff Group. We suggest that they may have come from the erosion of parts of the Whitehills Group which lie 5,000 to 8,000 feet below the boulder-bearing horizon.

Discussion

Source of the Boulders.—The trondhjemitic and granodioritic rocks are not distinctive enough for their source to be identified. They do show, however, that at the time the Upper Dalradian was being deposited, a terrain where plagioclase-bearing rocks were present must have been exposed. Some such land mass could have supplied certain of the constituents of the typical Upper Dalradian grits and greywackes which are characteristically rich in plagioclase. J. G. C. Anderson (1947, p. 505) has, for instance, deduced that U. Dalradian sediments along the Highland Border were derived from a land mass which " consisted largely of coarse granite or orthogneiss of an acid, dominantly sodic, type ". The Banffshire boulders might well have come from such a land mass. The syenites have not been identified with any possible source.

The siliceous metamorphic rocks might represent parts of the Moine Series, but could equally well be matched with some of the Lewisian altered sediments or with the types found as boulders in the Torridonian.

The possibility that the limestone might be derived from earlier

Dalradian types has been mentioned. The Upper Dalradian sediments, with their frequent thick graded beds, which we regard as products of submarine density currents, and their slumped deposits, appear to have accumulated during a phase of crustal instability. It is possible that during this phase sufficient uplift occurred for earlier parts of the Dalradian succession to be exposed outside the trough in which the Upper Dalradian was accumulating. If the Macduff boulder-bearing greywacke really contains fragments of the Whitehills Group, then a quite considerable uplift must have taken place by the time that it was deposited. We hope to discuss this question in more detail elsewhere.

Transport of the Boulders.—The problem of the transport and deposition of the boulders may be summarized as follows: (1) they occur in graded greywackes of a type that is abundant throughout much of the Banff Division, but nowhere else have these greywackes been found to contain such boulders. (2) The boulders are mostly of crystalline rocks and consist entirely of types foreign to the immediately underlying beds. (3) The matrix is far more abundant than the boulders, much finer in grain, and appears to have been laid down before the boulders were introduced.

There is no doubt that the greywackes form part of a sequence of marine deposits and of one that, as we hope to show in a separate publication, may have accumulated in deep water. The disparity in size between the pebbles and boulders and the largest grains in the matrix, together with the fact that the boulders disturb the bedding of the deposit, seem to suggest that the boulders were carried to the sea-floor by some other agency than that transporting the material of the greywacke matrix.

The forces capable of depositing large and relatively infrequent boulders in a deep-sea sediment are limited and the most likely agencies seem to be volcanoes, turbidity currents, and floating ice. The possibility that the boulders were ejected from a volcano can be discounted, in the absence of any trace of ash, lava, or other volcanic products in the associated sediments.

We have suggested elsewhere that the thick graded grit beds which alternate with finer-grained rocks throughout much of the Banff Division were brought down and deposited in deep water by the action of repeated turbidity currents, and it might be postulated that such currents had transported the boulders seen at Macduff. We have considered this possibility very seriously and have rejected it for the following reasons. In the first place, the boulders appear to have been added to the deposit after it had been laid down. Secondly, boulders have only been found in two localities, although the greywacke in which they occur is of a type widely developed in the Banff Division. It seems therefore that the boulders were not transported by the agency that

carried the matrix of the beds. The possibility that the boulders were dropped from exceptionally strong turbidity currents depositing a younger bed and then sank through the unconsolidated sediments under their own weight into these rather fine-grained greywackes has been considered. The absence of disturbance above the boulders, the fact that large and small boulders lie side by side, together with the circumstance that the upper parts of a number of graded beds are particularly rich in boulders all suggest that the fragments did not travel downwards through great thicknesses of unconsolidated sediment below the sea-floor.

By a process of elimination we arrive at the likelihood that the boulders were carried by drifting ice, from which they fell into deposits which were being laid down by turbidity currents. Ice-borne fragments reached the bottom while some twenty to thirty graded beds formed, giving an approximate idea of the relative importance of the two means of deposition. Arguing from estimates made by other writers of the rate at which graded greywackes accumulated, the boulder-bearing beds at Macduff might conceivably record 20,000 to 50,000 years' sedimentation.

Comparable Occurrences :—Late Pre-Cambrian glacial deposits have been reported from many areas around the north Atlantic. The literature has been summarized by Kulling (1951) who regards these deposits as dating from a period he has named the Varanger ice age. Kulling has described tillites lying unconformably on Pre-Cambrian gneisses in Scandinavia to the east of the Caledonian fold belt. These are taken to represent a till laid down on land. Within the Eocambrian of the mountain chain a number of occurrences of tillites, usually as massive, unstratified, unsorted beds intercalated conformably in normal sedimentary sequences, have been reported. These presumably mark localities where glaciers reached the sea, where marine sedimentation was interrupted for a time and substantially all the deposit was glacial in origin. A third category occasionally recorded, recalls the Banffshire boulder-bearing bed ; in this type, normal sedimentation continued but was punctuated from time to time by the arrival of ice-rafted erratics. The resulting deposit consists of bedded sediments with occasional boulders. In the late Pre-Cambrian Hecla Hoek Succession of New Friesland, for example, fine-grained slates containing pebbles and boulders up to 2 feet in diameter were found by Fleming and Edmonds (1941) on the east side of Gorge Valley. The finer material forms a uniform matrix " into which the boulders have dropped directly from melting icebergs, so that they occur sometimes infrequently and at other times in profusion " (Fleming and Edmonds, 1941, pp. 417–418).

Other instances of boulder-bearing beds which might be comparable to the Banffshire example are the Permian shales and sandstones

with erratics of the Lower Hunter River District, N.S.W., where boulders believed to have been rafted by icebergs occur in rocks containing well preserved fossils (David 1950, vol. 1, pp. 337–338).

Boulders thought to have been carried by ice have been dredged from the oceans around Antarctica. Recently Menard recovered boulders up to 20 × 30 × 33 cm., from sea mounts in the Pacific and concluded that in Pleistocene time glacial marine drift was deposited over several hundred thousand square miles of the north-eastern Pacific (Menard 1953, p. 1279, p. 1284).

The Stratigraphical Position of the Banff Boulder-bearing bed.—The age of the Dalradian is at present a matter of dispute and it has been suggested that parts of the series may be Pre-Cambrian, Cambrian, or Ordovician.

It would at present be quite impossible to attempt to correlate the Banff boulder-bearing bed with any other deposit, but it remains a fact that the Eocambrian glacial deposits found in Scandinavia, Spitzbergen, and Greenland are all apparently earlier than the lowest fossiliferous rocks, though they are probably spread over a considerable period of Pre-Cambrian time. It would appear therefore that however long glaciation lasted or however often it was repeated it had ended by lower Cambrian times. This might suggest that the Banff deposit was probably earlier than the lowest Cambrian. As against this must be set the fact that of all glacial deposits ice-borne erratics of this nature would be the most widespread in time and would continue to be deposited after tillite formation had ceased.

Should the Banff boulder-bearing bed, which lies comparatively high in the Upper Dalradian sequence, prove to date from some Eocambrian ice age, then the base of the Cambrian must lie somewhere above this deposit and the greater part of the Dalradian in N.E. Scotland would be of late Pre-Cambrian or Eocambrian age.

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Notes on the Ultrabasic Body of Unst, Shetland Islands

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Abstract

Within the main serpentine of Unst, a lower peridotite layer, a dunite layer, and an upper pyroxenite layer can be distinguished. These three zones have transitional contacts which are marked by a primary mineral banding. Analyses of specimens from each zone are given and it is suggested that the layering is due to differentiation *in situ*. The zones dip steeply eastward and the base of the intrusion is cut off on the west by a thrust which is slightly oblique to the banding and locally cuts out the peridotite zone. Interior planes of dislocation are parallel to, or perpendicular to, the primary banding.

Introduction and Previous Work

THE ultrabasic rocks of Unst, in the Shetland Islands, form a broad belt running S.S.W.–N.N.E. along the length of the island for

Text-fig. 1.—The Serpentine and Greenstone Blocks of Unst.

a distance of about 8 miles. To the east of this belt lies a body of altered basic rock, and the whole mass of basic and ultrabasic rocks forms a tectonic unit to which Read (1934) gave the name of the Main Serpentine and Greenstone Block. The block is bounded by two major planes of dislocation which separate it from the metamorphic sediments on the west and south-east sides (Text-fig. 1). A smaller thrust block of serpentine, the Clibberswick Serpentine Block, lies to the north.

The work of Phillips (1927) and later of Read (1934) has established an outline of the magmatic and subsequent metamorphic history of the ultrabasic rocks. Both writers described a zonal structure in the body,

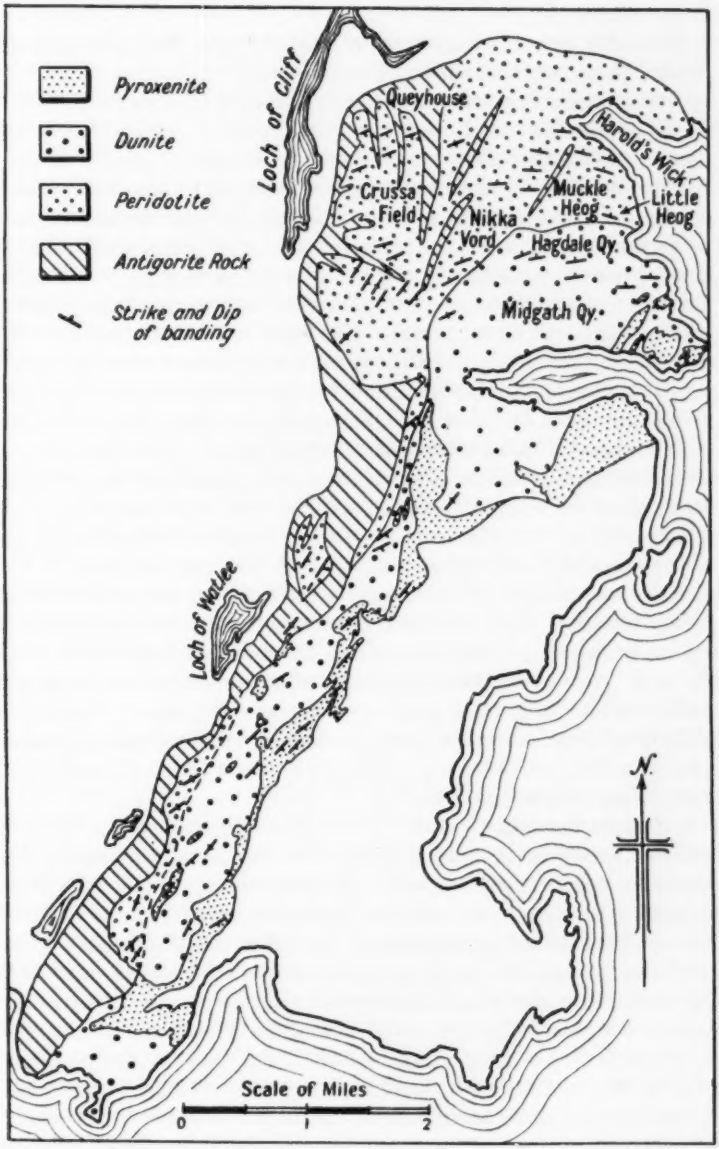
the rocks being stated to pass gradually from serpentine derived from dunite on the western side to pyroxene rock on the eastern side. Both workers regarded the gabbro which succeeds the pyroxene rock on the east as a slightly later intrusion, although Read concluded that the actual contacts were mechanical.

Secondary alterations, including the production of fibrous serpentine, antigorite serpentine, talc-, talc-magnesite-, and tremolite-schists were described. Phillips regarded the majority of these changes as auto-metamorphic, concluding that contemporaneous dynamic action was responsible for the formation of the antigorite ; he regarded the talc-schists as products of later dynamic action. Read, on the other hand, found that antigorite serpentine was developed in a thick belt along the western boundary of the ultrabasic mass, and along certain belts within it ; in both cases it was often associated with talc-rich schists. He showed that the belts of antigorite lay along lines of thrusting and concluded that the mineral and the associated talc-bearing rocks had been formed after the general serpentinization by dislocation metamorphism accompanying the formation of the thrusts. The thrust bounding the Serpentine Block was considered to be one of a number of major dislocations dividing the island of Unst into a number of separate blocks, each of which had its own metamorphic history.

The present writer has recently completed a study of the ultrabasic rocks of the Serpentine Block and the purpose of this paper is to record some new facts concerning their primary and secondary features. The mass has been found to consist not of two, but of three main zones—a peridotite layer, which forms the lowest zone against the marginal thrust on the west, a dunite layer, and an upper pyroxenite layer. These zones pass gradually into one another and a mineral banding marked by concentrations of pyroxene in certain laminae is developed at many localities, especially along the zone boundaries. This banding has an arcuate trend, which is parallel to that of the three major zones and is cut across by the basal thrust plane. Little need be added to previous accounts of the general serpentinization ; the excellent metamorphic differentiation shown by talc-chlorite-carbonate rocks in the shear-zones has already been described (Amin, 1952).

Primary Characters of the Ultrabasic Mass

The most westerly of the three composition zones (Text-fig. 2) consists of peridotite and dips steeply eastward beneath the dunite zone, which in turn passes under the pyroxenite zone. From the south of the island to Balta Sound, the peridotite and dunite zones run north-north-eastward ; they swing round into an easterly direction north of Balta Sound. The pyroxenite zone shows no corresponding deviation



TEXT-FIG. 2.—Geological Map of the Unst Serpentine.

of strike and continues north-eastward until it runs out to sea at Swinna Ness.

The sense in which the terms peridotite, dunite, and pyroxenite are used in these pages is as follows :—

Peridotite : dominant olivine and rhombic pyroxene.
Dunite : „ olivine.
Pyroxenite : „ diopsidic pyroxene.

All the rocks are more or less completely affected by autometamorphic changes as a result of which the primary minerals are pseudomorphed by serpentines, chlorites, and tremolite. Relics of the original minerals are preserved, the diopsidic pyroxene being particularly resistant to alteration, and the mode of replacement is such that the primary textures can still be examined. The absence of disturbance of the textures and the uniform distribution of the changes make it appear probable that the fluids responsible for the metamorphism originated within the rocks and that the transformations were thus, as Phillips (1927) suggested, autometamorphic. The antigorite rocks described by Read (1934) as products of dislocation metamorphism, on the other hand, show no relics of primary textures, and it is clear from their relations that these rocks were formed after the general serpentinization.

The *Periodite Zone* reaches a thickness of 3–4 miles in the north and dwindles to a fraction of a mile in the south ; it is entirely absent east of Loch of Watlee. The variations in thickness of the zone appear to be caused by the oblique trend of the basal dislocation which cuts it off to the west. For a considerable distance above the thrust the rocks are converted into massive or schistose antigorite-serpentine. North-east of Loch of Watlee the antigorite rock encloses a serpentine lenticle more than half a mile long, in which the junction of the peridotite and dunite zones can be recognized.

A distinct banding produced by the concentration of pyroxene in certain layers is observable in parts of the peridotite zone and is best developed near its junction with the dunite zone. At Harold's Wick the rock is very uniform ; as one approaches the top of the zone on Muckle Heog the banding appears first as faint lines detectable only on weathered surfaces where the pyroxenic layers stand out as hard ribs. The width of the bands and the degree of concentration of the pyroxene increase towards the boundary of the zone. Strong banding can be seen at Little Heog, Muckle Heog, Nikka Vord, and in the chromite quarries west of Crussa Field and at Queyhouse. Weaker banding can be seen at many other localities and the strike and dip of the structure are recorded in Text-fig. 2, where it can be seen that the banding is parallel to the top of the peridotite zone.

The bands vary in width from a fraction of an inch to 6 feet ; their length is generally proportional to their width and ranges from a few

feet to 100 feet. The bands are always roughly parallel and although they lens out along the strike and occasionally divide they never cross one another. Their margins are fairly sharp, although the crystals interlock across the boundary ; graded structure was not observed.

In the peridotite serpentines of the peridotite zone olivine, altering to serpentine mesh, forms 40–50 per cent of the rock ; very altered pyroxene which appears to be orthorhombic makes up 25–35 per cent and the remainder is composed of small quantities of diopsidic pyroxene like that of the pyroxenite zone, chromite (2–4 per cent), and secondary interstitial antigorite.

The *Dunite Zone* attains a maximum width of 2 miles north of Balta Sound and narrows southward to half a mile or less. Lenticular patches of dunite, up to 500 feet in length, like in the upper part of the peridotite zone, with their long axes parallel to the mineral banding and to the zone boundary. There is often a marked banding at the contact of these enticles with the peridotite.

Schlieren of chromite-rich rock and large lenticular bodies of massive chromitite, which are now almost entirely quarried away, can be found in many parts of the dunite zone, and the distribution of old quarries seems to indicate that workable concentrations of chromite are confined to this zone and to the dunite patches in the peridotite zone. The quarries at Hagdale and Midgarth lie in the middle of the dunite zone, the chain of quarries between Muckle Heog and Nikka Vord are on the dunite-peridotite margin and the Queyhouse and Crussa Field quarries worked chromite from dunite lenses in the peridotite zone.

The dunite serpentine, which is the dominant rock of the zone, consists of olivine grains altering to mesh serpentine, with accessory chromite.

The *Pyroxenite Zone* forms an irregular belt running north-east along the eastern side of the ultrabasic mass. The passage from dunite to pyroxenite takes place through a transitional layer of olivine pyroxenite. Lenticular or irregular bodies of pyroxenite, often with sharp boundaries, occur in the transitional zone and in the dunite zone (Text-fig. 2). Thin veins or dyke-like bands of pyroxenite traverse both the dunite and the peridotite in the region north of Balta Sound.

A banding of the olivine pyroxenite is produced by the concentration of the pyroxene in certain lamellae. The strike of this banding is conformable with the banding in the dunite zone, but it is oblique to the trend of the pyroxenite zone in the region north of Balta Sound.

Diopsidic pyroxene, resembling the mineral found in accessory amounts in the peridotite zone, is the dominant mineral of the pyroxenite zone. This mineral (2V 59°–61°, Z $\wedge$ c 38°–39°) is partially altered to serpentine, antigorite, and tremolite. In the transitional olivine-pyroxenite the olivine occurs as rounded grains and the

pyroxene forms irregular grains filling the interstitial spaces; it evidently crystallized later than the olivine.

It appears from the facts discussed above that the peridotite, dunite, and pyroxenite zones are in natural contact with one another and that the contacts are transitional and not intrusive. The ultrabasic body has therefore probably, as Phillips suggested in 1927, undergone differentiation *in situ*. Both Phillips and Read (1934) considered that the base of the body was on the west. This interpretation is confirmed by the prevalent easterly dip of the banding. East of Queyhouse and Crussa Field, however, the banding passes through vertical and begins to dip to the north; in this region the dunite zone dips beneath the peridotite zone and it seems probable that the zones are overturned here.

TABLE I

	A.	B.	C.
SiO_2	39·82	33·03	47·64
Al_2O_3	1·14	0·46	1·25
FeO	3·98	3·48	2·49
Fe_2O_3	3·67	4·85	2·23
Cr_2O_3	0·28	1·02	0·66
CaO	2·06	nil	16·24
MgO	38·17	41·08	24·18
K_2O	tr	tr	tr
Na_2O	nil	nil	0·27
$H_2O - 105°$	0·42	0·74	0·37
$H_2O + 105°$	10·36	14·67	4·39
	99·90	99·33	99·72

A. Peridotite serpentine, Clibberswick.
B. Dunite serpentine, Hagdale.
C. Antigorite-bearing pyroxenite, Swinna Ness.

Analyst: W. H. Herdsman.

The dip of the banding is everywhere steep, as is the boundary thrust. Since the metamorphic sediments of Unst are also mostly steeply dipping (Read, 1934), it is possible that the serpentine zones originally lay more nearly horizontal and that they were produced by gravity stratification. Since the Serpentine Block rests on a thrust its true base is never seen.

Crystallization of the peridotite, which forms the lowest visible layer, seems to have been followed by a phase of extreme differentiation in which the dunite, with concentrations of chromite, was formed. At the top of the dunite zone the relations of olivine and diopsidic pyroxene in the transitional olivine-pyroxenite suggest that the olivine crystallized first and that the pyroxene was deposited from a magma in the interstices between the grains. It is possible that the two lower zones were formed by accumulation of crystals and that the residual magma concentrated at the top of the body to form the pyroxenite zone. That

a pyroxenite magma was available is suggested by the occurrence of irregular sharp-edged masses and of pyroxenite veins in the lower zones.

The composition of specimens from the three zones is given by the analyses in Table I. All the specimens are partly serpentinized, which accounts for the high percentage of H_2O. The dunite is poorer in silica and lime and richer in magnesia than the underlying peridotite. Silica and lime increase greatly in the pyroxenite and magnesia shows a corresponding decrease. The alteration in the Ca : Mg ratio at this stage marks the first appearance of abundant monoclinic pyroxene. Since the pyroxene is diopsidic, alumina remains low.

Thrusting and Dislocation Metamorphism

(*a*) *The Dislocation Belts.*

Read (1934) has described the steeply-dipping boundary thrust of the Serpentine Block, which runs north-north-east from Wick of Belmont to Loch of Cliff, and a number of interior belts of dislocation which he considered to lie either parallel or perpendicular to the boundary of the mass. The position of these dislocations, marked by belts of antigorite rock, can be seen from the writer's map (Text-fig. 2). The boundary thrust cuts obliquely across the primary structures of the ultrabasic mass. East of Loch of Cliff the thrust runs north-north-east, whereas the mineral banding strikes east-north-east. Near Loch of Watlee the peridotite zone is completely cut out by the thrust.

The interior dislocations, on the other hand, tend to run either parallel or perpendicular to the mineral banding, and their development seems to have been controlled by the primary structure of the mass. These dislocations are concentrated in the region where the strike of the zones swings round from a north-north-easterly to an easterly direction, and this part of the intrusion must have been one of abnormal stress. The reversal of dip north of Balta Sound may have been effected by movements on the dislocation planes.

Many rocks within the belts of dislocation are schistose and the schistosity is, as Read (1934) observed, most often oblique to the trend of the dislocation, both in the boundary thrust and in the minor thrusts. The strike of the schistosity is commonly north-east–south-west and the dip is towards the south-east. The parallelism of the schistosity in the boundary thrust and in the interior dislocations confirms the suggestion that these structures and the metamorphism associated with them are all of the same age.

(*b*) *Dislocation Metamorphism.*

The formation of thick belts of antigorite rock and of talc-carbonate- and tremolite-schists along the lines of movement has been described by Read, who concluded that the rocks were the products of dislocation

metamorphism accompanying the thrusting. The exact type of rock formed appears to depend on the composition of the parent rock. Thus, in the peridotite zone, antigorite rock is formed above the main thrust and talc-magnesite rock actually along the thrust. In the dunite zone, antigorite and antigorite-magnesite rocks are more common than talc rocks, and magnetite-rich schlieren with decomposing chromite grains representing the chromitite schlieren are widespread. In the pyroxenite zone antigorite-tremolite rocks with or without carbonate are formed.

Except where they are crossed by localized shear-planes the antigorite rocks are generally massive. The fluids responsible for the alteration appear to have migrated along the dislocation belts and then to have moved outward into the surrounding rocks. It is noteworthy that the interstitial antigorite in the peridotite serpentine increases greatly in amount towards the interior belts of dislocation. It appears that stress alone was not responsible for the formation of antigorite, but that the mineral was produced by migrating fluids whose passage was facilitated by shearing.

Along actual movement planes the rocks produced by dislocation metamorphism are generally schistose. The development of a strong schistosity appears to have increased the mobility of the penetrating fluids, for it is sometimes accompanied by metamorphic differentiation as a result of which lenticular bodies of pure talc, magnesite, or chlorite are formed. This metamorphic differentiation has been described in detail by the writer (Amin, 1952).

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CORRESPONDENCE

ON THE OCCURRENCE OF LINNAEITE IN THE COAL MEASURES OF SOUTH WALES

SIR,—In 1928 the *Geological Magazine* published a note [1] on linnaeite following a paper [2] by Dr. F. J. North and the writer on the distribution of millerite in South Wales. The records of occurrence are, of course, of academic interest only. The more important significance is the light which the occurrence of these minerals throws on the source of the sediments deposited in what is now South Wales during Coal Measure times.

In the 1928 [1] paper, I remarked that the only previous record of Welsh linnaeite which I could find takes the form of a note (without title) by A. L. des Cloizeaux in a French publication.[3] This record was based on a specimen from the " Rhonda " (Rhondda) discovered by a Mr. Terrill of Swansea, " which does not seem to have been preserved."

I visited the Museum d'Histoire naturelle in Paris and was most kindly received by Dr. Orcel, who gave me access to the reserve collections. I failed to find the specimen as it never occurred to me that it might still be in the collection made by Mr. Terrill.

In 1937 the Terrill collection of minerals was presented to the National Museum of Wales, but after ten years the name had no particular significance for me and it was not until 1951 when the collection was being critically examined that I discovered a specimen of linnaeite from South Wales and realized the Terrill who made the collection and the Terrill referred to by des Cloizeaux in 1880 were one and the same person.

The specimen in the Terrill collection is no better than those described in 1928, and it has no information giving the precise horizon and locality.

The specimen consists of separate crystals or aggregates of minute modified octahedra on dolomite or ankerite lining septarian cracks in clay ironstone.

I have now confirmed the occurrence in Wales of all the minerals found in similar circumstances in the clay ironstones of Bohemia with the exception of whewellite, hydrated calcium oxalate. The specimens kindly given to me for the National Museum of Wales by Professor Slavik from the Prago Mine, near Kladno, Bohemia, show the whewellite to be the last formed mineral and it way well be that the Bohemian mineral is of very recent origin, possibly associated with the decay of pitprops in abandoned workings.

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12th July, 1954.

ANGLE BETWEEN THE PRINCIPAL HORIZONTAL STRESS AND TRANSCURRENT FAULTS

SIR,—By a coincidence two papers recently published in the same number of the *Geological Magazine* (xci, 2) provide evidence that under some conditions the angle between the principal horizontal stress and transcurrent faults is about 60° and not, as suggested by Anderson (1942, p. 14), always less than 45°.

In Leedal and Walker's map (p. 118) of transcurrent faults cutting the Barnesmore Granite in Donegal the average strike of the dextral faults is 086° and that of the sinistral faults 218°. If these faults were caused by the same stress conditions, the direction of the principal horizontal stress is $\frac{1}{2}(218° + 086°) = 152°$, and the angle between the principal stress and the fault $\frac{1}{2}(218° - 086°) = 66°$. Because this angle is greater than 45°, and without confirmatory evidence, Leedal and Walker concluded that the two sets of faults are of different ages.

A map presented by Auden (p. 98) shows dykes and two sets of shear (transcurrent) faults cutting Deccan lavas in Bombay State. If it is accepted with Anderson (p. 24) that the dykes lie in the general direction of the principal horizontal stress, then one of the sets can be distinguished as dextral and the other as sinistral, in spite of the fact that no displacements have been determined. The average strike of the dextral is 021° and that of the sinistral 141°. The direction of principal horizontal stress is $\frac{1}{2}(141° + 021°) = 081°$, and the angle between the principal stress and the faults $\frac{1}{2}(141° - 021°) = 60°$. The average strike of the dykes is 072°, 9° less than the strike of the horizontal principal stress determined from the faults.

The examples given have the disadvantage that being "fossil" faults it is difficult to prove that the dextral and sinistral members are parts of the same stress pattern. Active faults do not suffer from this disadvantage.

Two suitable pairs of active transcurrent faults are known in New Zealand—the Alpine and Moonlight faults (Wellman, 1953), and the Wellington and Baring Head faults—by a coincidence they give the same direction of stress and the same angle—112° and 57°.

The evidence from active major transcurrent faults in California is similar to that in New Zealand. The sinistral Big Pine and Garlock faults are intersected by the dextral San Andreas Fault (Hill and Dibblee, 1953), the stress directions being 354° and 356° and the angles 65° and 68°.

The angles between the principal stress and the transcurrent faults are remarkably consistent and considerably in excess of the maximum value of 45° suggested by Anderson from theory. It is suggested that observations be made over as wide a range of tectonic conditions as possible and an attempt then made to establish a more comprehensive theory.

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15th July, 1954.

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MINERALS FOR THE CHEMICAL AND ALLIED INDUSTRIES

Sir,—I deeply appreciate the general tenor of Professor Fearnsides's review (*Geol. Mag.*, xcl, 1954, p. 334), of my recently published book, *Minerals for the Chemical and Allied Industries*, but would like to correct a misunderstanding.

Professor Fearnsides states that: "A good many of the essays were written and published in a technical journal when the author was Principal of the Mineral Resources Department of the Imperial Institute, and Head of the Commodities Intelligence Section of the Ministry of Economic Warfare. The information selected from official files is tersely put . . ." This might be interpreted as meaning that while I occupied an official position I used official records for private purposes. This was not the case. Actually, none of the essays was written until after I retired from my official position in May, 1946, and the assistance I received later from the Mineral Resources Department of the Imperial Institute was such as is available to any member of the public wishing to use their Information Service, which includes a good technical index and reference library. I do not think that this Service is sufficiently well known.

As indicated in the Preface, all the articles as published between August, 1946, and February, 1949, were revised and considerably enlarged before publication in book form with additional chapters.

During my long association with mineral development work, however, I was fortunate to make contact with a large number of experts engaged in the chemical and mining industries who, after my retirement, kindly supplied much valuable up-to-date information for inclusion in my book. In fact, over thirty of the chapters were "vetted" by technical experts in this country and the U.S.A.

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PROPOSED NEOTYPE FOR *PLEUROTOMARIA ANGLICA* (J. SOWERBY)

SIR,—I should be glad if you would allow me to announce in your columns my intention (failing the receipt of information as to the whereabouts of the two figured syntypes) of designating and figuring a neotype of the species *Trochus similus* J. Sowerby (1816, *Mineral Conchology*, **2,** pl. 142), the name of which was altered to *Trochus anglicus* in the Corrigenda in the same volume; this species has long been referred to the genus *Pleurotomaria*. The syntypes are not in any institution known to me to possess Sowerby types, but could conceivably have found their way to a provincial museum or teaching collection. Sowerby did not state who sent them to him, or from which of four localities mentioned in his text they came, but it is most probable that the larger specimen (the other consisted merely of the external and internal moulds of a shell) came from the Middle Lias of White Lackington Park, near Ilminster; in which case it was presumably collected (as were other specimens from this locality described by Sowerby) by E. Strangewayes or Strangeways, after whom *Ammonites strangewcysi* was named. I cannot say if E. Strangeways was connected with the Fox-Strangways family.

I should be most grateful for any information about the missing specimens or the present whereabouts of the E. Strangeways Collection, as it is, of course, essential that every effort should be made to trace original types before having recourse to the procedure for designating neotypes decided upon at the 1953 International Congress of Zoology at Copenhagen.

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RULES OF NOMENCLATURE

SIR,—My letter on clause 54 (1) (*a*) of the "Copenhagen Decisions" (*Geol. Mag.*, 1954, xci, p. 174) was not written without previous discussion with other workers, all of whom agreed with my view, and I have since had letters of support from institutions and individuals as far apart as the United States and New Zealand. Dr. Sabrosky (*Geol. Mag.*, 1954, xci, p. 325) is the first to suggest that we have "misread the decision and misjudged its effects".

This contention appears to me to be quite untenable, for the decision taken by the Copenhagen Congress at the outset of its revision of the Articles of the Code relating to family names, namely the decision to revoke the existing Articles 4 and 5 (1953, Copenhagen Decisions on Zoological Nomenclature, page 32, decision 43) can only mean that the new provisions then adopted apply to all family names, irrespective of the date on which they were published. I therefore cannot accept Dr. Sabrosky's assertion that we have misjudged the effects of the Copenhagen decision.

Apart from this, clause 54 (1) (*a*) seems to me to be wrong in principle, for it states as a Rule that wrong names are to be used in preference to correct ones. We all recognize that any rules must at times produce an unfortunate result in particular cases, and that such cases should be adjusted by a special act of the Commission under its plenary powers. No limit has been set to the number of such cases that may be brought forward for individual legislation. It is not, however, the *correctly* formed names that should be suppressed by Rule and require this protection to survive, but the nomenclaturally incorrect names, i.e. those formed on junior synonyms. As remarked in my previous letter, the Rule should state the obvious, which is that the name of a family is to be formed on the valid name of its type genus.

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September, 1954.

THE MIOCENE/OLIGOCENE BOUNDARY IN THE CARIBBEAN REGION

SIR,—The paper by F. E. Eames in this Magazine (vol. xc, No. 6, December, 1953), and the subsequent exchange of opinions between Drs. Eames and Stainforth (vol. xci, Nos. 2 and 4), are of unusual interest to students of Caribbean stratigraphy.

Eames certainly demands drastic changes in the Upper Tertiary stratigraphy of the Caribbean region but there is no sense in trying to shirk the issue at stake. We are not in a position to contradict his contentions but it seems prudent and scientific to consider seriously his conclusions. Is it only a coincidence that almost all specialists in larger foraminifera with intimate knowledge of faunal assemblages in Europe, North Africa, and the Near and Far East, were, and seemingly still are, inclined to attribute a younger age to post-Eocene larger foraminifera from the Caribbean region than is admitted by their colleagues in the Americas? Why the common reference of students of smaller foraminifera to the close relationship of Miocene-Pliocene assemblages of the Indo-Pacific with Oligocene ones of the Caribbean region? In the Paleocene and Eocene we accept without hesitation the fact that pelagic forms may be used as universal time markers. There is, therefore, no reason why the same or related genera should not have the same stratigraphic value in younger beds. At least until the end of the Oligocene there was free connection between Atlantic and Pacific provinces across the Darian isthmus (Woodring, 1954, p. 728). This being the case there was nothing to stop free interchange between the two areas at this period, let

alone between North Africa and the Caribbean region. It is, therefore, necessary to heed the advice of Eames and review and assess the palaeontological evidence of the Caribbean region without preconceived ideas.

Above all we have to agree with Eames who states that the type locality of the Aquitanian must be in the Aquitaine and nowhere else. Secondly, we must reconcile ourselves to the fact that European Tertiary stages are established essentially on the study of shallow water marine molluscs and therefore must disagree with Gignoux (1936, p. 503), who—though tentatively only—places the Aquitanian in the Upper Oligocene on account of the Stampian aspect of a mammalian fauna of the lacustrine facies equivalent of the marine type section. Following from these two suppositions we have to place the Aquitanian in the Lower Miocene (see Rutsch, 1952, p. 354), as in fact is done by the U.S. Geol. Survey (Woodring, 1943, p. 1714). Many of the discrepancies found in attempts to make a worldwide correlation of the Upper Tertiary would disappear if universal agreement could be reached on this point.

The boundary between Oligocene and Miocene in Trinidad has recently been discussed (Kugler, 1953, p. 46), when it was pointed out that, in reality, the zone of *Globorotalia fohsi* belongs in the Lower Miocene and not in the Upper Oligocene as under the present classification used in the Island. If, however, " the evolutionary succession of *Miogypsina* sensu stricto lies entirely within the Miocene " (Eames, 1954, p. 327),[1] then hardly any sediments occurring in Trinidad could be assigned to the Oligocene, for in such case the *Globigerinatella insueta*, the *Globigerina dissimilis*, and the *Globigerina* cf. *concinna* zones would be of Miocene age. The *Globigerina* cf. *concinna* zone includes the oldest *Miogypsina* s. str. bearing sediments in Trinidad and at its type locality contains a rich orbitoid fauna (Stainforth, 1948, p. 1310). Although no Miogypsinae are recorded from the calcareous silts of the type locality, Vaughan and Cole (1941) report *Miogypsina hawkinsi* and *gunteri* from eleven different localities of lithothamnia limestone and interbedded marls with the same, or a very closely related, orbitoid fauna characterized by the *Lepidocyclina gigas*, *undosa*, *favosa* assemblage. From three of these localities (Kapur, Morne Diablo, and Mejias) Drooger (1952) reports *Miogypsina basraensis*, *tani*, and *bronnimanni*. Tobler (1925) mentioned *Miogypsina* from Mejias and Erin Point in association with the above mentioned large Lepidocyclinae and attributed an Upper Oligocene (Aquitanian) age to this assemblage. Whereas the Orbitoid fauna of the type locality of the *Globigerina* cf. *concinna* zone occurs in situ, all other post-Eocene occurrences mentioned from Trinidad are from slipmasses embedded with other allochthonous material in the *Globigerina dissimilis*, *Globigerinatella insueta*, and *Globorotalia fohsi* zones and even in the Karamat and Cruse formations. Trinidad is, therefore, not suitable for the study of the lineage of Miogypsinae. Antigua would serve this purpose better.

W. P. Woodring, in his classical study of the Bowden formation in Jamaica, considered the fauna to belong to the Vindobonian stage, or in terms of American stratigraphy, to the top of the Middle Miocene or to the base of the Upper Miocene. P. Bronnimann studied the foraminifera of ten samples from the type locality and in a private report assigned all of them to the *Globorotalia mayeri* zone which is confined to the Lower Lengua formation of Trinidad and to a basal subzone of it which is known from Trinidad to occur at the base of the Tamana limestone formation. On this information one would expect the Middle and Lower Miocene to be represented by those Tertiary sediments that are found in normal sequence of several thousand feet thickness below the Lengua formation.

The *Globorotalia fohsi* Zone of the Cipero Formation unconformably underlies the *Globorotalia mayeri* zone. The neritic facies of the *Globorotalia fohsi* zone includes the Brasso Formation with a molluscan fauna which has been assigned to the Miocene by Guppy, Mansfield, Maury, and others.

[1] Again indirectly suggested by Drooger (1954, p. 246).

Orbulina, the Miocene marker, does not occur below the *fohsi* zone. The *Pleurophopsis–Thyasira* fauna mentioned by Stainforth (1948, p. 1311) from Freeman's Bay, and placed by him in the *Globorotalia fohsi* zone, occurs in thin, nodular, calcareous mudstones and lenses of cavernous limestones, both embedded in calcareous clays of the *Globorotalia mayeri* zone of the Lengua Formation. There is no evidence that these coldwater bivalves are allochthonous, although the Lower Lengua Formation is known to carry submarine slipmasses and rubble of older Cipero beds.

The *Globigerinatella insueta* Zone of the Cipero Formation follows below the *fohsi* zone and in its shallow water facies is characterized by the reefal limestones of Ste. Croix and the Esmeralda calcareous silt member of the Brasso Formation. Rutsch (1934) studied the pteropods of these beds and pointed to their evident relationship to the Italian Burdigalian (Langhian) and Helvetian.[1] Schilder (1939), who studied the Cypraeaceae of the Adivinanza quarry (an impure limestone near the Ste Croix limestone and of the same age), attributes a Burdigalian age to them. The corals of these two reefs were considered to be Miocene by Vaughan and Hoffmeister.

The *Globigerina dissimilis* Zone of the Cipero Formation follows normally below the *insueta* zone with the Nariva Formation representing its muddy fore deep facies. The *dissimilis* zone is commonly contaminated with allochthonous material produced by submarine land-slides and turbidity flows. The *Lepidocyclina gigas, undosa, favosa* assemblage of orbitoids occurs together with *Miogypsina* in the limestone of Kapur, which, according to Bronnimann (private report) and Drooger (1952, p. 21), represents a shallow water facies of the *Globigerina dissimilis* zone. However, at this locality this zone also carries reworked material of Upper Eocene and Middle Eocene age, as well as foraminifera of the *Globigerina* cf. *concinna* zone.

Miogypsina complanata is reported by Drooger (1951, p. 363) from Trinidad. According to Bronnimann (private report) this form occurs in the *Globigerina dissimilis* zone and Caudri (in Stainforth, 1948, p. 1312) reports it from the limestone and marl of Mejias Quarry. The Mejias limestone slipmass is found embedded in the *Globigerina fohsi* zone.

The *Globigerina* cf. *concinna* Zone [2] follows normally below the *dissimilis* zone and, as already mentioned, at the type locality carries an orbitoid fauna of the *Lepidocyclina gigas, undosa, favosa* assemblage which Vaughan and Cole (1941, p. 28) consider to be of Upper rather than Lower Oligocene age. The poor molluscan fauna of seven species was studied by Rutsch (Stainforth, 1948, p. 1310) and the age was determined tentatively as either Rupelian or Chattian. The most common species is *Propeamussium bronni pennyi* (Harris) which is also found in younger beds. In addition, J. W. Wells (private letter) mentions the coral *Trochocyathus* (*Aplocyathus*) *obesus* (Michelotti) from the type locality. The orbitoid fauna of the type locality shows great similarity in composition to that of Mejias, Kapur, and other limestone slipmasses of South Trinidad. This assemblage is closely related to that of the type locality of the Antigua limestone in Antigua and the San Luis limestone in the State of Falcon (Venezuela). J. W. Wells who studied the coral fauna of the Antigua limestone mentions in a private letter thirty-three different species. Of these he noted six species amongst the fourteen listed from Kapur Quarry. Three of the species from Kapur also occur amongst the twenty-five species of the San Luis limestone. The coral fauna of Antigua is considered to be Oligocene. The Antigua limestone rests unconformably on stratified tuffs with cherts bearing a typical fresh-water molluscan fauna and beautifully preserved silicified wood of a comparatively rich flora. At San Fernando (Trinidad) the orbitoid assemblage of *Lepido-*

[1] Drooger (1954) correlates the " Langhiano " and " Elveziano " of the piedmont area of Turin with the upper part of the Aquitanian of the Bordeaux area.

[2] Bolli (1954) described *Globigerina* cf. *concinna* as *Globigerina ciperoensis* and in future the zone has to be called accordingly.

cyclina gigas, undosa, favosa rests directly on the Upper Eocene (Stainforth, 1948, p. 1309). In reality, one observes at the type locality of the San Fernando Formation, at Mt. Moriah, well bedded, calcareous, glauconitic sands of Upper Eocene age superimposed on Middle Eocene Navat Formation, Paleocene Chaudiere shale, and Upper Cretaceous Naparima Hill Formation. These glauconitic sands are unconformably overlain by a block conglomerate, about 20 feet thick, dominantly composed of Upper Cretaceous blocks. This conglomerate changes rapidly upwards into sand and silt of apparently Upper Eocene age, including bioherms of Upper Eocene orbitoidal lithothamnia limestone rich in echinids (*Echinolampas*) and a few molluscs. A few large blocks of Maestrichtian glauconite sand, blocks of Paleocene Soldado Formation and of Senonian Naparima Hill Formation are embedded in these sands and silts. These Upper Eocene beds grade upwards into the *Globigerina* cf. *concinna* zone.

Up to now no definite Lower Oligocene sediments have been established in Trinidad, although it is known that foraminiferal calcareous sediments exist between the cf. *concinna* zone and the Upper Eocene. Similar uncertainties are known from Venezuela where the Guacharaca Formation of the Agna Salada Group (Renz, 1948, p. 30) might belong to it.

There is obviously every reason to expect the presence of sediments of the entire Oligocene time where carbonate deposits were being laid down from Upper Eocene times into the Oligocene.

Woodring (1954, p. 727) states that in the Caribbean region " an early Oligocene part has not yet been faunally defined ". It appears that one of the first steps to be taken is to define the age of the Antigua limestone with its rich assemblage of larger foraminifera, corals, echinoids, and a few molluscs. Such definition of age has, however, only a meaning if palaeontologists and stratigraphers can arrive at an agreement regarding the top of the Oligocene and cannot be solved by coining new stage names based on foraminiferal assemblages; a procedure that can only lead to chaos in stratigraphic nomenclature. Agreement has generally been reached as regards the base of the Oligocene inasmuch as the top Eocene pelagic foraminifera are universally widespread and well-defined. The definition of the top of the Oligocene is of sufficiently great importance to deserve the attention of the International Geological Congress and it is hoped that this question may be taken up in 1956. In Mexico, geological conditions for the solution of this problem are amongst the best to be found. A world-wide correlation of Tertiary marine sediments based on pelagic foraminifera is the ardent desire of most micro-paleontologists and geologists.

Until more compelling evidence is available, and the whole matter is discussed at an international meeting, I consider that the base of the Caribbean Miocene should be placed temporarily at the base of the *Globorotalia fohsi* zone.

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24th September, 1954.

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REVIEWS

GEOCHEMISTRY. By the late V. M. GOLDSCHMIDT. Edited by ALEX MUIR. pp. 730. Clarendon Press, Oxford, 1954. Price 63*s*.

V. M. Goldschmidt died in 1947 after a long illness resulting from severities suffered as a prisoner in Norway under the Nazi occupation of World War II. Most of the *Geochemistry* was written in hospitals and nursing homes in Britain and it was unfinished on the author's untimely death at the age of 59 years. The difficult task of filling in gaps in the manuscript, adding notes of later work relating to the problems therein discussed, and the assembling of scattered Goldschmidt material to produce an integrated whole has been most successfully accomplished by the Editor and a large number of helpers of whom Dr. S. R. Nockolds, Dr. J. R. Butler, and Professor C. E. Tilley may be especially mentioned. The result is a handsomely produced volume which is a worthy monument to one who did so much to develop the science of geochemistry and impress geologists with its importance and fascination.

" Modern Geochemistry," in Goldschmidt's words, " studies the distribution and amounts of the chemical elements in minerals, ores, rocks, soils, waters, and the atmosphere, and the circulation of the elements in nature, on the basis of the properties of their atoms and ions." The greater part of this work (Part II) is a discussion of the geochemistry of the individual elements. For each one, where appropriate, there is an account of its abundance and distribution in igneous rocks and minerals, hydrothermal rocks, metamorphic rocks, meteorites, sedimentary rocks (grouped as residual, hydrolysate, oxidate, calcareous, and evaporate), weathered products including soils, marine and fresh waters, and the atmosphere. The theory of the principles which control the occurrence of the elements, and their behaviour under geological processes is treated in Part I under the headings of distribution of the elements during the evolution of the earth, evolution of the magmatic rocks, the chemical composition of the cosmos, and some principles of crystal chemistry in relation to geochemistry.

Goldschmidt was primarily a geologist and it is that which makes his treatment of geochemistry so valuable to geologist readers. It is impossible here to refer to the many illuminating side-lights thrown on geological data, but to mention one point only it is interesting to note that Goldschmidt, contrary to current opinion, in referring to the rarity of intermediate rock types in gabbro and granite provinces, considers that a magma in taking up water may separate into two liquids—an anhydrous gabbroid magma and a hydrated granite magma. Goldschmidt's outlook on science is revealed in a footnote (p. 594) from which we quote: " We must never expect perfect agreement between observed facts and the predictions of theory which always has to have a simplified basis . . . In case of conflict you not only can be assured that facts are invincible, however inconvenient they may appear, but you can also be sure that the greatest incentive to scientific progress is the clear consideration and utilization of the differences between observed fact and current theory . . . You can never force your opinion against facts, but in alliance with facts progress is yours. As an experienced skipper has to look for any impediments such as adverse currents and wind, and must try to make them serve his voyage, so a leader of research or a teacher of science has to look out for conflicts serviceable for progress. No theory is perfect in itself, every fact *is*, when observed and recorded in an honest manner."

One does not, of course, have in this book any treatment of the most recent developments of geochemistry concerned with the distribution of the isotopes of the elements and later speculation regarding the composition of the earth's interior; but the volume is complete in itself, an indispensible work of reference, and of absorbing interest to all students of earth processes and development.

L. H.

PETROGRAPHY. By H. WILLIAMS, F. J. TURNER, and C. GILBERT. pp. 416 + numerous figures. Freeman and Co., San Francisco, 1954. Price $6·50.

This book, for students who have a knowledge of optical mineralogy, is intended as a textbook for a course of one academic year's duration on the study of rocks in thin section and in hand specimen.

It is divided into three sections (Igneous, Metamorphic, and Sedimentary), and is illustrated by some 400 excellent drawings of thin sections. After a brief introductory chapter on magmatic processes a summary chapter is devoted to textures, structures, and the classification of igneous rocks. This is followed by five chapters in which the rocks are grouped according to a " clan " principle, within each clan the fine-grained and coarser grained rocks being considered. Were a student to study no more igneous petrology than that given, the presentation is attractive and the description of the rock types is in general adequate.

For students intending to do further work this section is poor and does not provide an adequate systematic basis of petrographic data for studying problems of rock genesis.

The authors have rejected an overall mineralogical scheme of classification (however artificial) with the result that the mutual relations of one rock type to another are not clear. In its place is substituted five all-embracing clans based on a few clear and many debatable genetic associations, and in which are associated rocks so diverse as to be unrelated petrographically or genetically.

There is a complete absence of any chemical data either on rocks or minerals, the appreciation of which is an essential part of the petrographic background for students of rock genesis.

The section on metamorphism is a concise statement of the metamorphism of the principal rock types and some effort is made to integrate this with the " facies classification ". If there is any criticism to be made it is that perhaps the sequence of changes on progressive metamorphism of any one rock type is not emphasized enough, and that at least one A.C.F. diagram—say of the Pyroxene Hornfels facies—should have been presented and discussed. For in these the variation of mineral assemblage with bulk chemical composition is better appreciated than in tabulated statements of mineral assemblages.

The section on sedimentary rocks is an exceptionally well presented statement which could hardly be bettered. The chief weaknesses are in the treatment of glacial sediments, and in residual deposits. An omission, which will be regretted by European students, is that there is no reference to the chalk.

In the introduction the authors state that the paucity of references to original literature throughout the book is essentially to save space for illustrations. This has been a wrong decision. If a geological book is intended for university students, even first year ones, references to the original literature should be quoted.

By their insertion the student becomes familiarized with the names of petrologists, the journals in which original work is published, places where rocks occur, and the time at which work was done. A stimulus is provided for the student to read at least some original works which reacts favourably on his appreciation of Petrography, and its place in geological studies, and also cultivates his critical faculties in a way which is not provided by reading further textbooks. This is particularly so where the Memoir, or Journal, describes an area which it is possible for him to visit.

S. O. A.

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